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A Distributed Hydrologic Model of The Woodlands, Texas: Modeling Hydrologic Effects of Low Impact Development

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ABSTRACT

A Distributed Hydrologic Model of The Woodlands, Texas:

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This thesis utilizes a distributed hydrologic model to predict hydrologic effects of Low Impact Development (LID), and also analyzes runoff from small sub-areas within the watershed. City planners and developers rely on accurate hydrologic models, which enable them to design flood-proof developments and effectively mitigate flooding downstream. Common hydrologic models use a lumped approach, which averages the physical characteristics of basins for model calculations, limiting their ability to estimate runoff within the basin. In contrast, distributed hydrologic models, which divide the watershed into a grid system, can be used to predict runoff at any location within the watershed. The fully distributed hydrologic model, *Vflo*™, is used to model stormwater runoff in The Woodlands, TX watershed, and to demonstrate the effectiveness of the master planned community. This thesis also suggests that a calibrated *Vflo*™ model can accurately predict stormwater runoff from small sub-areas within a watershed.

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1 Introduction and Background

Today urban sprawl is a common issue faced by many states, where rapid development is consuming green space, promoting auto dependency and widening urban fringes, ultimately putting greater pressure on environmentally sensitive areas (EPA 2000). Urban development has no doubt played a significant role in changing the hydrologic cycle, primarily by increasing the area of impervious surfaces, becoming a challenge for developers to mitigate increased urban runoff. “As watersheds are urbanized, their surfaces are made less pervious and [the systems become] more channelized, which reduces infiltration, speeds up the removal of excess runoff, [and allows for more severe pollutant loadings]” (Holman-Dodds et al. 2003; Lee and Heaney 2003).

Runoff volume increases during urbanization as a result of soil compaction and construction of new roads, parking lots and buildings. The traditional method for managing this increased runoff is to collect all runoff in gutters, which funnel water into a conveyance system of concrete channels and pipes, carrying water away as fast as possible into a receiving stream, lake, or ocean. This has been successful in reducing local flooding problems, but in some cases, increased peak flow rates have caused severe flooding in areas downstream. Not only do impervious surfaces cause increased runoff in urban areas, they also accumulate on their surface, pollutants which are easily removed by runoff, in turn resulting in decreased water quality within the watershed. Although it has been known that hydrologic characteristics of a watershed change during and after urbanization, the reduction in water quality as a result of urbanization was not recognized until the late 20th century (Dinez, 1979). Reports and case studies now exist to provide strong evidence that urbanization negatively affects streams and results in water quality problems such as loss of habitat, increased temperatures, sedimentation and loss of fish populations (USEPA, 1997).

In recent years, Low Impact Development has been highly touted as an alternative approach to stormwater management. Numerous studies have analyzed different development scenarios that aim to manage runoff from impervious surfaces and to promote infiltration on site (Holman-Dodds, 2003; Williams, 2006; Harrell, 2003; Goff, 2006; Li, 2011; Brander, 2004). In addition to effectively managing stormwater and reducing runoff, infiltration-based development may also increase recharge of local ground water aquifers and streams, reduce erosion and stream widening, and improve steam water quality (Prince George's County, 1999). However, the concept of an infiltration-based development is not new. An oilman by the name of George Mitchell had a vision in the 1960's for a development that preserved pre-development hydrologic conditions while creating a sense of community without all the hustle and bustle of urban living. Mitchell did not like the typical 'helter-skelter, fragmented development' that did not use its natural surroundings; instead, he wanted to build a 'pleasant, healthy, and harmonious place for people of low-to-high income to live' (Morgan, 1987). His vision, an example of Low Impact Development (LID) before the concept became popular, is now called The Woodlands, TX, Texas's most celebrated master-planned community.

The Woodlands development was master planned to protect its natural resources and existing hydrology, as envisioned by George Mitchell. The heterogeneous landscape of the development includes forest, river bottom, lakes and detention ponds, residential areas, and commercial areas, which can be difficult for hydrologic models to represent accurately. A distributed hydrologic model, called *Vflo*™, is used in this thesis to model the varying landscape of The Woodlands, and to prove the effectiveness of its drainage design.

Hydrologic models incorporate watershed parameters through space and time, enabling hydrologic transport and storage processes to be calculated through the use of well-known numerical methods. Hydrologic models can simulate the rainfall-runoff processes in a watershed, which is a valuable tool to watershed protection plans and development design. Advances in computer hardware and software since the 1970s and major strides taken in hydrologic data monitoring have significantly benefited hydrologic models. Modern hydrologic computer modeling software can be generally categorized as lumped or distributed, as will be discussed in more detail later. Fully distributed hydrologic models provide the ability to simulate the spatial variability of hydrologic processes over the landscape of a watershed, whereas lumped models assume homogeneity across the area.

Advancements in physically based hydrologic modeling, radar rainfall technology, and GIS spatial data processing allow detailed representation of varying land uses and development scenarios within a watershed model, advancing the ability of planners to quantify changes in infiltration and runoff on a scale previously inhibited by lumped modeling approaches. It may be possible for fine-scale, distributed models to be used as a design tool for urban communities, to mitigate the effects of development on runoff, while more effectively maintaining pre-development hydrologic conditions, as shown in this thesis

This study established two calibrated, fully distributed hydrologic model of The Woodlands, TX watershed in its undeveloped and current development conditions, as well as creating a hypothetical development model. The three models were used to compare the rainfall-runoff response of the watershed with different development scenarios, consisting of different imperviousness and land cover. The Woodlands watershed serves as a good case study because of the development's innovative master plan approach that was well ahead of its time. The master plan included numerous sustainable drainage designs, which are now considered Low Impact Development. George Mitchell's vision for The Woodlands was innovative at the time and has laid the foundation for what is now deemed Low Impact Development.

1.1 Summary of Objectives

This thesis employs a distributed hydrologic model and the Rational Method to analyze stormwater runoff in The Woodlands watershed to achieve the following objectives:

1. Build and calibrate a distributed model for The Woodlands watershed in its current development conditions.
2. Build and calibrate a distributed model for The Woodlands watershed in its pre-development conditions.

3. Build a distributed model of The Woodlands watershed to represent a hypothetical scenario with concrete channels and a highly impervious development.
4. Compare the three models to evaluate the success of The Woodlands in preserving pre-existing hydrology in the watershed.
5. Assess the ability of a calibrated distributed model to accurately predict peak flows from small sub-areas within a watershed.

Next, this thesis will provide details about The Woodlands development and its history. It is important to understand the concepts that were integral in the design of The Woodlands, because it was one of the first sustainable developments and is highly touted for its achievements. Newer developments are being master planned with environmental sustainability in mind, such as the Cross Creek Ranch in Fulshear, TX (Cross Creek Ranch, 2012). Low Impact Developments are becoming more common, and The Woodlands should be used as a model for sustainable watershed management.

1.2 The Woodlands, TX

George Mitchell was the head of a diversified energy company with significant real estate ventures, and he was familiar with signs of inner-city decay, which he began seeing in downtown Houston. Mitchell began realizing his dream of a new community development when his firm began purchasing land in the 1960s, settling on an area north of the intersection of FM 1960 and I-45. The total land acquisitions included four major tracts of land and numerous smaller deals, resulting in an average land cost of $1,688 per acre (Morgan, G., 1987). The Woodlands development plan received approval from the

U.S. Department of Housing and Urban Development, and in 1974 The Woodlands was founded as a 28,000 acre master planned community. Figure 1-1 below shows the location of The Woodlands watershed north of Houston, also identifying the USGS stream gage used in this research. USGS gage 08068450 is located near the outlet of the watershed at Sawdust Rd. (see Figure 2-1), and has recorded daily streamflow data since 1972. Since The Woodlands' foundation, water quality and discharge rates have been monitored with stream gages, and it has been host to extensive water quality research.

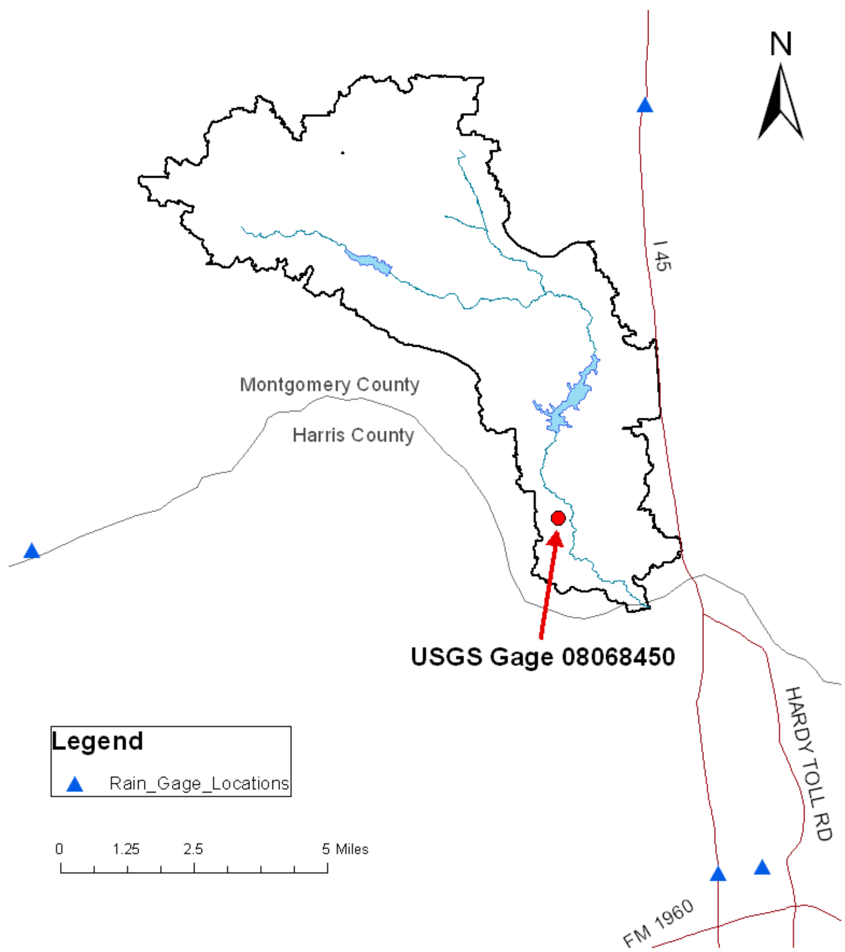


Figure 1-1 The Woodlands watershed location north of Houston, TX and USGS stream gage near outlet

The development plan of The Woodlands was unique because it aimed to preserve and utilize the natural landscape for flood control. Figure 1-2 is an image of a natural drainage pathway preserved in The Woodlands. These valuable resources were protected in The Woodlands as opposed to other developments who converted riparian corridors into concrete conveyer belts.

Figure 1-2 Natural drainage pathway preserved in The Woodlands development

"Planning stormwater management in advance has the advantage of reserving land for alternative measures of flood control. In most developed watersheds, remedial measures for flood control are often difficult to implement due to land restrictions in upstream areas" (Bedient, Flores, Johnson, & Pappas, 1985). To help design the drainage of The

Woodlands, a study was conducted by Bedient (1985) using HEC-1 hydraulic computer modeling to evaluate various development options. The study resulted in recommendations for the drainage design and placement of reservoirs to meet George Mitchell's objectives.

Mitchell believed that the two key components to his new development were to maintain the forest and the hydrologic cycle. He assembled a group of scientists and developers together, who came up with the following seven goals for land-use planning of The Woodlands (Morgan & King, 1987):

1. Minimize disruption of the surface and subsurface
2. Preserve the woodland
3. Maintain the natural drainage system with floodplains, swales, ponds, and recharge
4. Preserve vegetation noted for species diversity, high quality, stability, and uniqueness
5. Provide wildlife habitat corridors
6. Minimize development cost
7. Avoid hazards to human life or health

The Woodlands began attracting residents in 1974, and has experienced consistent growth and development since. In 1980 The Woodlands reported having 8,400 residents after only six years on the market, and today the community hosts over 97,023 residents and 40,550 households. Residents are attracted to The Woodlands due to its natural beauty, 160 miles of hike and bike trails, 6,000 acres of green space, retail shopping and entertainment, jobs, and schools. The average income for families living in The Woodlands is $110,000 and it is recognized as one of the top 10 safest communities in Texas (Woodlands, 2012). This sense of community is what Mitchell had been dreaming about, but the development would not be possible without the advanced stormwater management planning to offset the effects of development.

The master plan for The Woodlands has received much recognition for its superb design and its quality lifestyle. The Woodlands was one of the first sustainable developments ever built in the U.S., and the seven development goals used to plan the community are similar to the guidelines for what is now known as 'Low Impact Development.' The Woodlands master plan design was well ahead of its time, and should be used as a model for future developments.

1.3 Low Impact Development

Low Impact Development (LID) is a relatively new concept in stormwater management, pioneered in the 1990's by Prince George's County, Maryland (USEPA, 2000). LID principles are growing in popularity, but are not widespread, largely due to their infancy and lack of public understanding. The goal of LID design is to maintain or replicate the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape. "Hydrologic functions of storage, infiltration, and ground water recharge, as well as the volume and frequency of discharges are maintained through the use of integrated and distributed micro-scale stormwater retention and detention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time" (Coffman, 2000). LID design techniques also include protecting environmentally sensitive site features such as riparian buffers, wetlands, steep slopes, mature trees, flood plains, woodlands and highly permeable soils. Figure 1-3, adopted from Chang (2010), gives a simplistic design of a watershed consisting of both LID and stormwater best management practices. This simplified watershed management plan protects the natural riparian and wetland areas, which help retain water on site and improve water quality. In addition, detention basins are implemented to help attenuate peak flow rates during major storm events.

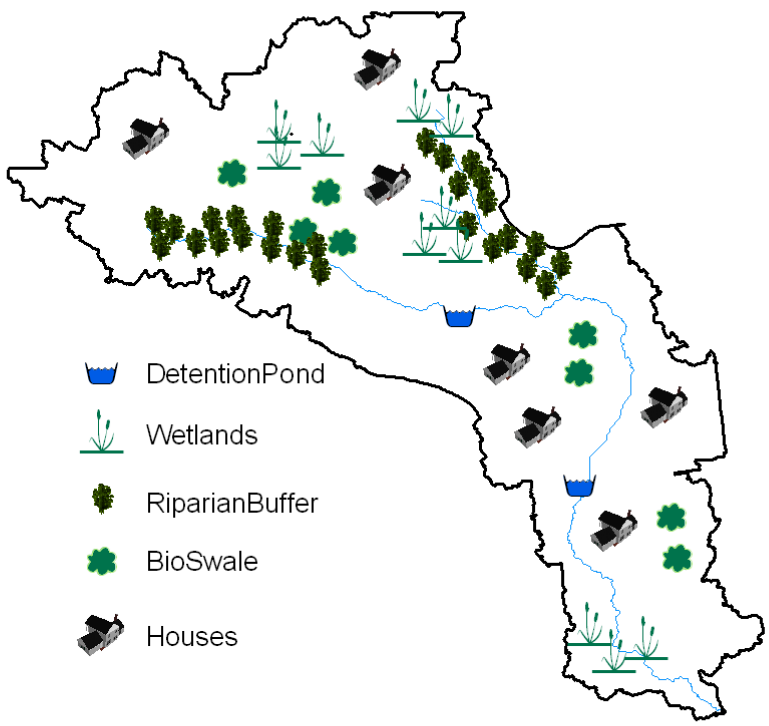


Figure 1-3 Simplified design of a watershed with various LID concepts

Unlike conventional stormwater management, which has been applied to rapidly sprawling urban development, LID aims to control stormwater runoff on site. Conventional stormwater management involves a system to collect, convey and discharge runoff as efficiently as possible; ponding water on the surface is not desirable and should be removed immediately. In conventional systems, water is funneled downstream and managed in large facilities located at the base of drainage areas (USEPA, 2000). However, these design concepts may be at the cost of water quality, local aesthetics, and downstream flooding. An analysis of historical water data for the rapidly developing Cypress Creek watershed indicates that the increased urban runoff and waste water discharge resulting from urbanization could potentially be linked to the water quality degradation of the watershed (Teague, 2011). Conventional practices may also result in inadequate base flows, thermal fluxes in the water body, and dangerous flash flood threats (Coffman, 2000).

On the other hand, LID may serve as an alternative not only because it can preserve the pre-development hydrology and cost less, but it can also be more aesthetically pleasing to the residents using the development. LID practices are more cost effective and lower in maintenance than conventional, structural stormwater controls (USEPA, 2000).

Depending on site characteristics such as soil permeability, depth of water table, and slope, various LID practices may be selected to manage stormwater on the site. “LID practices such as bioretention facilities or rain gardens, grass swales and channels, vegetated rooftops, rain barrels, cisterns, vegetated filter strips and permeable pavements perform both runoff volume reduction and pollutant filtering functions” (USEPA, 2000). The bioretention concept was developed in the early 1990’s by Prince George’s County, Maryland as an alternative to traditional stormwater management, by using a conditioned planting soil bed and planting materials to filter runoff stored within a shallow depression (Prince George’s County, 1999). The design considerations for bioretention, such as ponding area, planting soil, plant materials, etc., are carefully selected to maximize the physical filtration and biological processes. Design guidelines recommend that bioretention systems occupy 5-7% of the drainage basin (USEPA, 2000).

Another LID practice, grass swales or channels, are inexpensive and universal, and are most appropriate for smaller drainage areas with wild slopes (USEPA, 2000). These open channel systems have been traditionally used to transport runoff away from roadways, but can be optimized to effectively reduce runoff velocity and pollutant loadings. Modern optimization may include appropriate channel design, slope, length, and Manning's roughness value, which are determined from local site conditions. Contrary to the typical curb and gutter/storm drain inlet and storm drain pipe systems, these engineered grass swales are two to three times less expensive to install (USEPA, 2000).

Green roofs have the ability for on-site stormwater management, reduction of urban heat island effect, lowering heating and cooling costs of a structure, and increasing the longevity of the roof membrane. There is a need for research to further quantify the effectiveness of a green roof's performance in these tasks, which Rice University is currently undergoing. Some preliminary research has also been done in Chicago, Il. and Raleigh, NC. Initial findings from these two studies are that green roofs enable considerable savings in costs of heating and cooling, and that rainwater is effectively retained and peak flows are attenuated (North Carolina Sate University BAE Green Roof Research, 2004; Westerlund, 2006).

Case studies have provided preliminary evidence to support the effectiveness of these LID practices. A LID evaluation by Coffman (2000) used the following four hydrological functions to determine the effectiveness of LID practices: runoff curve number (CN), time of concentration (Tc), retention and detention. The following table adopted from Coffman (2000) summarizes the analysis of LID practices according to these components. Two key components of LID is to minimize the amount of rainfall converted into runoff and the increase the Tc, both of which help attenuate peak flows and improve water quality through infiltration.

Table 1-1 Low Impact Hydrologic Design and Analysis Components

	Low Impact Hydrologic Design and Analysis Components			
LID Practices	**Lower Post-Development CN**	**Increase Tc**	**Retention**	**Detention**
Flatten Slopes		X		
Increase Flow Path		X		
Increase Roughness		X		
Minimize Disturbances	X			
Flatten Slopes on Swale		X		X
Infiltration Swales	X		X	
Vegetative Filter Strips	X	X	X	
Disconnected Impervious Areas	X	X		
Reduce Curb and Gutter	X	X		
Rain Barrels		X	X	X
Rooftop Storage		X	X	X
Bioretention	X	X	X	
Revegetation	X	X	X	
Vegetation Presentation	X	X	X	

The runoff CN represents the runoff potential for a site, which is based on soil type, land cover and amount of impervious surfaces (Hawkins, 1998). LID practices intend to reduce or preserve the watershed CN, thus minimizing the amount of rainfall converted to runoff as a result of development. The Tc is the amount of time it takes for water to travel from the farthest point in a watershed to the outlet. Traditional stormwater management aims to decrease the Tc, which reduces the pollutant removal capabilities of the site and increases the peak runoff rate. Retention and detention are key to increasing the Tc in LID, and in turn increase infiltration, reduce peak flows, and reduce pollutant loading downstream.

Our understanding about the impacts of LID on stormwater volume and pollutant removal capabilities is still limited, but early evidence shows it may be a superior water management design tool compared to traditional methods. A comparison of runoff volume and quality from real storm events in an area where pre- and post-development conditions were monitored with and without LID practices would greatly advance our knowledge of these design practices. As more evidence emerges that supports LID, it will likely continue to grow in its application and may also be incorporated into certain design standards.

LID practices could also be strongly promoted if their effect on water quality and on runoff volume could be accurately modeled and predicted. A hydrologic model that could accurately predict these effects would allow planners and designers to confidently select the appropriate LID practices to achieve their stormwater goals.

1.4 Hydrologic Modeling

The premise of hydrologic modeling is to predict the response of a watershed to a specified rainfall input. Hydrologic models can be used to predict peak flows in a channel and to estimate inundated areas in the case of a flood event. The numerical methods that make up the backbone of these models were mostly developed during the 1950s and 1960s, and many new models have been developed since then.

Hydrologic models can be generally categorized into two different categories, lumped or distributed, depending on how the model handles spatial variability (Vieux, 2002). Lumped models do not consider the spatial variability of model inputs or outputs, rather they divide the watershed into sub-watersheds and average the parameters across the drainage area or stream length. Such models often use conceptual relationships to represent the rainfall-runoff process, ignoring the physical laws of the system, thus failing to account for internal variations of the hydrologic processes (Muzik, 1996; Vieux, 2004).

Some examples of lumped parameter hydrologic models that are common in the United States include the Hydrologic Engineering Center's HEC-RAS (U.S. Army Corps of Engineers, 2002), HEC-HMS (U.S. Army Corps of Engineers, 2001), and Technical Report-20 Model (SCS, 1965). The HEC-RAS software allows for one-dimensional hydraulic calculations in a network of natural and constructed channels. Computations within this software are based on the one-dimensional energy equation and the momentum equation. On the other hand, the HEC-HMS software is a hydrologic model designed to simulate the precipitation-runoff processes of watershed systems. The model is capable of calculating infiltration and routing runoff through numerous methods available to the user. A hydrograph is produced by the model at basin outlets, which can then be used by other software such as HEC-RAS. The simplicity of these models can be advantageous due to their fast computational time and ease of use, but if the spatial variability of the watershed parameters greatly affects the rainfall-runoff process, the use of lumped models may not be justified.

Another modeling approach, fully-distributed modeling, aims to ‘better represent the spatio-temporal characteristics of a watershed that transform rainfall into runoff, [in essence] replicating watershed behavior by building up components using conservation equations of mass and momentum” (Vieux, Cui, & Guar, 2004). The watershed domain is divided into smaller interconnected cells, assumed to be homogeneous, better preserving the spatial variation in slope, hydraulic roughness, infiltration, and rainfall input (Vieux, 2004). The parameters used to define the grid cells are capable of being derived from highly accurate digital databases and GIS technology. This accurate representation of the basin enables the model to better predict the response to a precipitation input. Even though there is still some degree of lumping in this method, re-sampling at a smaller resolution can only be justified if the information content improves (Vieux, Cui, & Guar, 2004). The issues of scale and spatial resolution become a pivotal issue, which is largely limited by computational capacity and availability of data.

1.5 Distributed Hydrologic Models

Distributed models are built on the elements of digital data, such as a raster digital elevation model (DEM), soils profile data, and land use data to define the drainage network parameters. “A DEM, which describes topography with a regular array of elevation data, captures a certain spatial variability based on the source of the data and the scale at which the data was measured and compiled” (Stewart, 2003). The elevation data is used to determine flow direction among grid cells, essentially connecting the cells for computation, and is also used to delineate channel corridors. Digital raster data for land use characteristics and soil types are input into the model, allowing the model to use physics-based equations to calculate infiltration and runoff. These physics-based calculations and the fully distributed approach make such hydrologic models important for assessing (1) the effects of land-use change and of spatially variable inputs and outputs, (2) the movement of pollutants and sediment, and (3) the hydrological response at un-gaged sites (Smith, et al., 2004).

Another advantage to distributed hydrologic models lies in their input of precipitation data. Precipitation, which is distributed in space and time, can be represented in the model by either interpolated rain gage data or radar rainfall data. Rain gage data, which only provides point data, can sometimes be sufficient for hydrologic modeling, especially considering budgetary restraints, but can often prove inadequate and unable to accurately capture the spatial and temporal variability of rainfall. Rain gages are also susceptible to human alterations and can malfunction during storm events. Recent applications of radar rainfall estimates have been used by hydrologists to overcome the inadequacies of rain gage data (Bedient, Hoblit, Gladwell, & Vieux, 2000).

NEXRAD (NEXt generation RADar) was originated in Norman, Oklahoma and first deployed at the full scale in 1992 (Fulton, Briendenbach, Seo, Miller, & O'Bannon, 1998). This technology is capable of estimating rainfall intensity from radar wave reflectivity, and provides spatially and temporally distributed rainfall data out to 230 km in 1 km intervals (Serafin & Wilson, 2000). The Accuracy of radar rainfall data is significantly improved through comparison to rain gage data and adjusting for systematic over- or underestimation (bias) of storm event rainfall accumulations (Vieux, Park, & Kang, 2009). A study by Teague (2011) compared streamflow predictions of a distributed hydrologic model using radar rainfall data or exclusively rain gage data. Results showed that the radar rainfall input was able to better match the observed streamflow, proving its advantage over exclusively using rain gage data.

Distributed hydrologic models have numerous advantages over other modeling approaches, but to what extent should such models be utilized? The following section discusses some of the limitations of distributed hydrologic models.

1.6 Distributed Modeling Limitations

As the quality and availability of digital data for hydrologic modeling improves, it is important to understand what the limitations are for fine scale and highly detailed distributed models. As stated by Vieux (2004), re-sampling at a smaller resolution can only be justified if the information content improves. In other words, what is the purpose of having a model that can represent every inch of the watershed if the accuracy/quality of the output does not improve? In addition, how well can a distributed hydrologic model predict runoff from small drainage areas within a watershed, even if using high resolution input data?

In general, DEMs and other spatial data of higher resolution can more accurately capture the variability in hillslope and hydrologic parameters, which are important in determining flow pathways and predicting runoff (Brasington & Richards, 1998). However, using the optimum model resolution is advantageous to avoid unnecessary computational restraints at the cost of minimal or zero benefit. Brasington and Richards (1998) conducted a sensitivity analysis of grid cell size within TOPMODEL, a distributed hydrologic model, and concluded that model predictions are resolution dependent.

Another study performed by Molnar and Julien (2000) analyzed two watersheds in Mississippi using the CASC2D distributed model. When cell sizes were increased in the model, the ratio of channel cells to total cells increased, resulting in channel flow being the dominant influence in the watershed. This is appropriate for large watersheds where channel flow is in fact the dominating factor, and coarse cell resolution will suffice in models. Further, a study by Vazquez et al. (2002) conducted a grid cell size analysis for the distributed MIKE-SHE model, using 300, 600, and 1200m cells sizes. The study concluded that the 600m model had the best overall performance, but the 300m model produced the best estimate of peak flows. Vazquez's study suggests that high resolution distributed models may not be the most efficient approach for stormwater modeling, but they may provide more accurate predictions of peak flows.

Distributed hydrologic models are applicable for many hydrologic modeling situations, and they can provide unique features that no other modeling technique can match. For this research, the fully distributed, physics-based hydrologic model, *Vflo*™, was selected to model land use changes in The Woodlands watershed. This thesis also explores the limitations of a calibrated *Vflo*™ model by analyzing peak flow predictions from small sub-areas within The Woodlands watershed. *Vflo*™ software has previously been used successfully in the Gulf Coast region, and is capable of predicting runoff from any cell within the watershed, which was desired for sub-area analysis (Duncan, 2011; Teague, 2011).

1.7 General Description of *Vflo*™ Model

Vflo™ is a fully distributed, physics-based hydrologic model capable of using geographic information to simulate the hydrologic response of watersheds (Stewart, 2003). "The origins of *Vflo*^{TM} were first described by Vieux (1988) whose finite element approach was expanded to include a network of elements representing both overland and channel flow in a watershed domain" (Vieux, Bralts, Segerlind, & Wallace, 1990) (Vieux & Gaur, 1994). Finite differences or finite elements methods are used to provide analytical solutions to the continuous equations involved in distributed modeling. Also, in order to compensate for some boundary conditions that may not be known, stochastic parameters having random variables with distributions in probability are introduced (Bedient & Huber, 2002).

DEM raster data, described previously, is the driving force of the model. The *Vflo*^{TM} watershed domain is divided into a grid system, where each cell is connected by flow direction arrows that are determined from the elevation data (Figure 1-3).

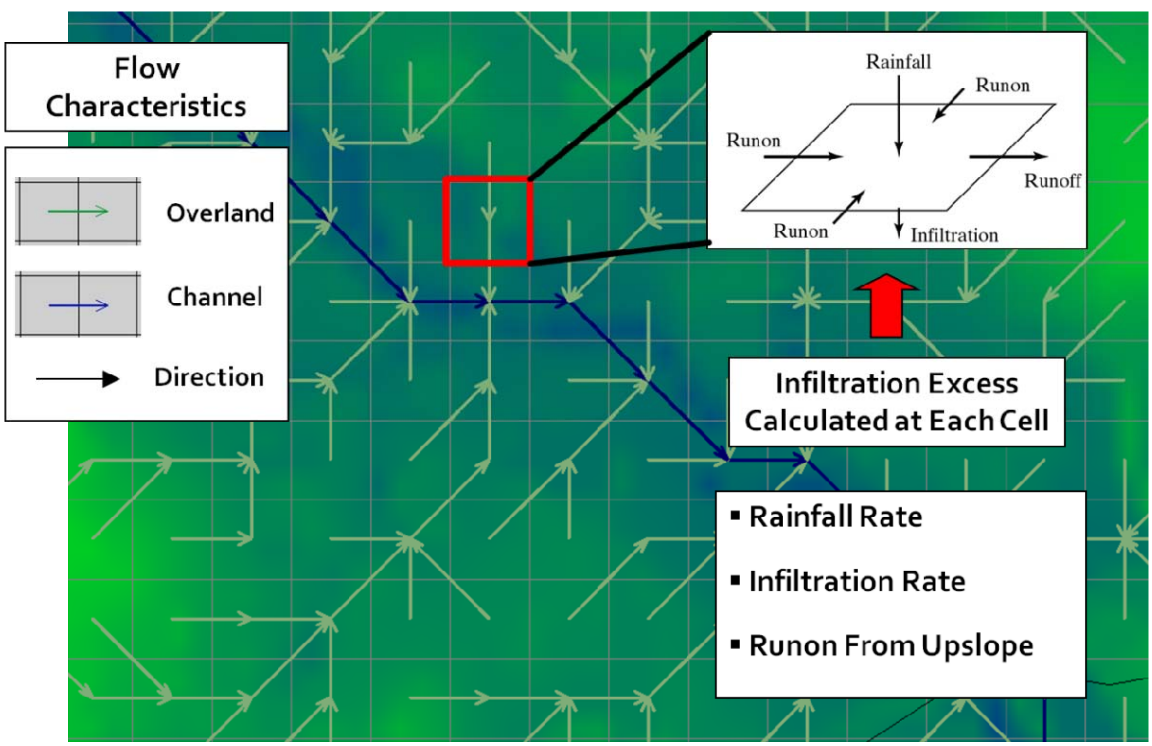


Figure 1-4 *Vflo*^{TM} grid cell system and cell components

Within each grid cell, *Vflo*^{TM} uses the conservation of mass and momentum equations to model the rainfall-runoff processes. The model is capable of computing any of the following runoff routing methods: the kinematic wave analogy (KWA), the diffusive wave analogy or the fully dynamical wave analogy, but the KWA was primarily used in this research and will be used for further discussion of the model. Within each cell established by the DEM, *Vflo*^{TM} uses the Green and Ampt Equation to calculate infiltration rate and infiltration excess (Eqn. 1-1), which is then routed in a network of overland flow and channel flow cells.

$$\boldsymbol{f = K_s\left(\frac{1-\psi\Delta\theta}{F}\right),} \qquad \textbf{Equation 1-1}$$

where K_s is the saturated hydraulic conductivity, ψ is the capillary suction head, $\Delta\theta$ is the moisture deficit, and F is the cumulative infiltration depth. The Green and Ampt equation was established in 1911 and has been used successfully to predict infiltration and runoff volumes in the lab and on small plot areas (Vieux B. E., 2004). For a constant rainfall, infiltration is treated as a two stage process in the Green and Ampt Equation. This first stage is considered the period for which the rate of infiltration exceeds the rate of rainfall, and the second stage begins once the rate of rainfall exceeds the rate of infiltration.

The parameters needed to solve the Green and Ampt equation can be determined in the lab or estimated from soil properties, which Bedient, Huber and Vieux (2008) state can be derived from digital soils data. The infiltration parameters derived from soils data are effective porosity, wetting front suction head, and saturated hydraulic conductivity. The parameters have been estimated from soil properties using regression techniques by Rawls et al (1983) and have been categorized for USDA soil textural classifications (Vieux B. E., 2004).

The parameters are used to calculate the time to ponding, which is the point in time when the rainfall rate exceeds the infiltration rate. Once the time to ponding is reached, all rainfall is converted into runoff and the finite elements method is used to develop a system of equations for solving the kinematic wave analogy (Stewart, 2003). “The finite-element method is an efficient way to transform partial differential equations in space and time into ordinary differential equations in time” (Vieux, Park, & Kang, 2009). The KWA routes overland flow and channel flow one dimensionally following Equation 1-2 (Vieux, Cui, & Guar, 2004):

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = r - i \text{ ,} \qquad \textbf{Equation 1-2}$$

where, *h* is flow depth, *u* is velocity, *r* is rainfall rate, and *i* is the infiltration rate. Velocity is solved using Manning’s equation, leaving *h* as the only unknown variable, allowing it to be solved at any grid location and time step within the watershed. The KWA assumes that channel flow is uniform and backwater effects can be ignored. This is generally true for areas with steep slopes and not applicable to flat areas, however, KWA has been successfully applied with *Vflo*^{TM} to watersheds throughout the Houston region (Vieux & Bedient, 2004). For more information regarding the *Vflo*^{TM} model, refer to Vieux (2004).

The Woodlands watershed model was constructed in *Vflo*^{TM} with 60m grid cells without overloading computer storage capacity because of the relatively small size of the watershed (34 mi^2). A *Vflo*^{TM} model for larger watersheds, such as Cypress Creek (308 mi^2), is more likely to have grid cell sizes in the magnitude of 300m (Teague, 2011). The high resolution grid for the Woodlands model allowed the model to account for high variability within the watershed, with the intention to predict runoff from small areas within the watershed. These small areas analyzed in this research did not have measured runoff data available to compare to *Vflo*^{TM} model predictions, instead the Rational Method was used as a benchmark comparison. The Rational Method was chosen because of its long-standing and undisputed use for hydrologic calculations in small urban areas.

1.8 Rational Method

The Rational Method was established in the 1850's and "is one of the simplest and best-known methods routinely applied in urban hydrology" (Bedient, Huber, & Vieux, 2008). The Rational Method is based on the assumption that a steady, uniform rainfall rate will produce the maximum runoff when the time of concentration (Tc) has been reached. A runoff coefficient, assumed constant during a storm event, reflects the runoff potential of a watershed, and is determined by the land cover of the area. Homogeneity of the land cover and rainfall over the area is assumed, limiting the method's application only to areas smaller than about 200 acres. The Rational Method equation is shown in Equation 1-3.

$$\boldsymbol{Q} = \boldsymbol{C} \times \boldsymbol{I} \times \boldsymbol{A}\,, \qquad \textbf{Equation 1-3}$$

where C is the runoff coefficient, I is the intensity of rainfall of chosen frequency, and A is the area. The runoff coefficient is selected from published literature and from professional experience, and is intended to represent watershed relief, soil infiltration, vegetation cover, and drainage surface characteristics (TxDOT, 2011). A single coefficient is selected for a drainage area, representing the entire area. The rainfall intensity coefficient for design storms is determined from time of concentration calculations.

2 Materials and Methods

2.1 Study Area

The Woodlands watershed is located within the Spring Creek drainage basin, and has a drainage area of about 34 square miles (Figure 2-1). The major stream draining The Woodlands is Panther Branch and is joined by its tributary, Bear Branch. Panther Branch and Bear Branch are intermittent streams with major no-flow periods during the summer months.

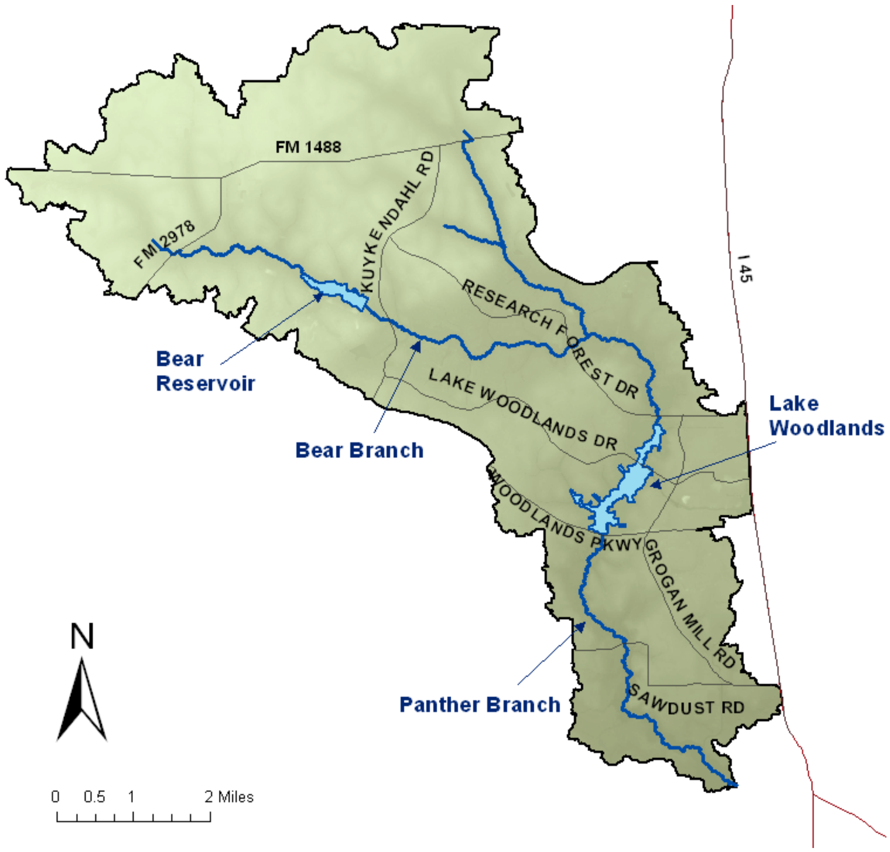


Figure 2-1 The Woodlands watershed and its water bodies

The watershed has generally mild slopes, averaging 2%, with the dominate soil type ranging from fine sand to loam. Throughout the development stages of The Woodlands, impervious areas were minimized and natural vegetation was preserved as much as possible. The watershed as a whole is comprised of 19% impervious surfaces, with the remainder comprised of developed open space and mixed forest type. Figure 2-2 below illustrates the 2006 Land Cover within the watershed (USGS Seamless Map Server).

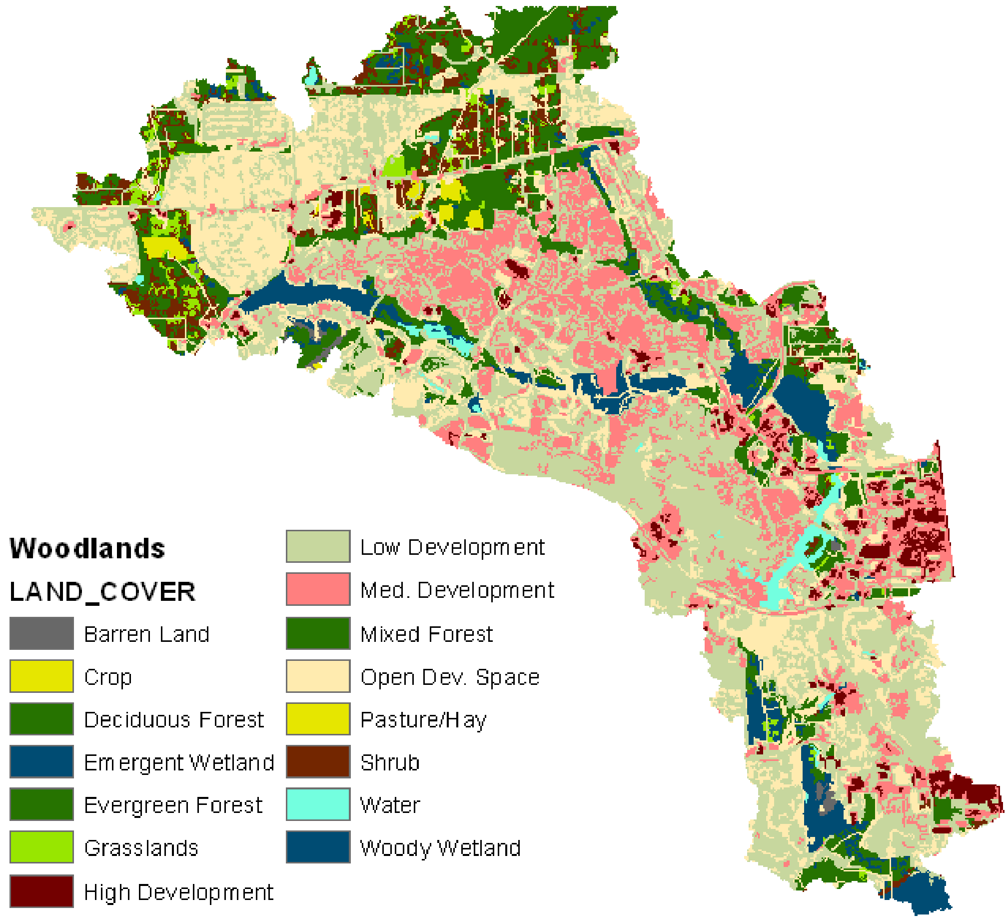


Figure 2-2 Land use and land cover types in The Woodlands watershed

The Woodlands watershed was selected because it is widely recognized for its innovative stormwater drainage design, and the effects of its development on water quality have been recorded for over 40 years. In addition, the watershed was sufficiently small enough to allow analysis of small sub-areas within the hydrologic model without burdensome computational requirements.

2.2 Model Development

Hydrology of The Woodlands watershed was modeled with the fully distributed hydrologic model, *Vflo*^{TM} (Vieux, 2004). Inputs required for *Vflo*^{TM} model development include elevation, land cover, and soils data, which must be preprocessed in GIS. These data were downloaded from publicly available sources online. Digital raster data for land use characteristics and soil types are input into the model, allowing the model to use physics based equations to calculate infiltration and runoff

Elevation data, which is used to determine cell slope, cell flow direction, and channel cross-sections, was obtained from the U.S. Geological Survey (USGS) Seamless Map Server (seamless.usgs.gov). This Digital elevation Model (DEM) came from the National Elevation Dataset and had a 5 meter resolution. The DEM was re-sampled to 30 meter resolution to reduce processing time and used to delineate the watershed boundary and drainage lines. The watershed DEM was imported into *Vflo*^{TM} as an ASCII file.

Soils data were obtained from the National Resource Conservation Service (NRCS) Soil Data Mart (soildatamart.nrcs.usda.gov). The soils data was preprocessed in order to derive the Green and Ampt infiltration parameters needed for *Vflo*^{TM}. The hydraulic conductivity and wetting front capillary pressure parameters were gathered for the appropriate soils types from Rawls, Brakensiek, & Miller (1983). Effective porosity and initial satural for the soil types were correlated with the values presented in Rawls, Brakensiek, & Saxton (1982). Lastly, soil depth was accepted as the thickness of the top layer in the soil data set. This data is presented in Table 2-1 below. Once preprocessed in GIS, these raster files were imported into *Vflo*^{TM} as ASCII files. The USGS National Land Cover Database 2006 Land Cover provided the most up to date land cover data for the model.

Table 2-1 Green and Ampt Infiltration Parameters

Soil Class	Effective Porosity	Wetting Front (in)	Hydraulic Conductivity (in/hr)
Fine sand	0.409	2.181	2.907
Loamy fine sand	0.407	3.374	0.803
Silt loam	0.486	6.567	0.256
Loam	0.434	3.500	0.134
Clay loam	0.309	8.220	0.039
Clay	0.386	12.453	0.012

The 30-meter USGS land cover data represented the varying land uses and imperviousness within the watershed, which helped create raster files of overland roughness and percent imperviousness by correlating land use with published values from Viuex, Inc. (2010) and TSARP (2003), shown in Table 2-2. The correlated land use files were imported into *Vflo*^{TM} as ASCII files.

Table 2-2 Manning’s roughness values and imperviousness

Land Use Description	Roughness (n)	Percent Impervious
Open Water	0.015	1
Open Developed Space	0.05	0.15
Low Development	0.015	0.2
Med. Development	0.015	0.4
High Development	0.015	0.85
Barren Land	0.04	0.05
Deciduous Forest	0.1	0
Evergreen Forest	0.1	0
Mixed Forest	0.1	0
Shrub	0.045	0
Grasslands	0.04	0
Pasture/Hay	0.055	0
Crop	0.035	0
Woody Wetland	0.06	0
Emergent Wetland	0.055	0

The AutoBOP feature in *Vflo*^{TM} was used to generate a new model of The Woodlands watershed. First the AutoBOP process interprets a DEM file to generate flow grids within the watershed. The user specifies the size and number of flow grids created within the model, which largely affects computational time when running the model. In this research, the cell size was set to 200 x 200 feet (60m), resulting in about 74,000 cells. Next, a channel threshold must be defined to establish what percentage of cells within the watershed should be channel cells. For The Woodlands, the channel threshold was established as 2%. Channel cells were also enforced according to a previously defined shapefile from GIS. All parameters previously discussed were imported into the AutopBOP as ASCII files, and channel cross sections were extracted from the DEM. Figure 2-3 illustrates how these input layers comprise a *Vflo*^{TM} model.

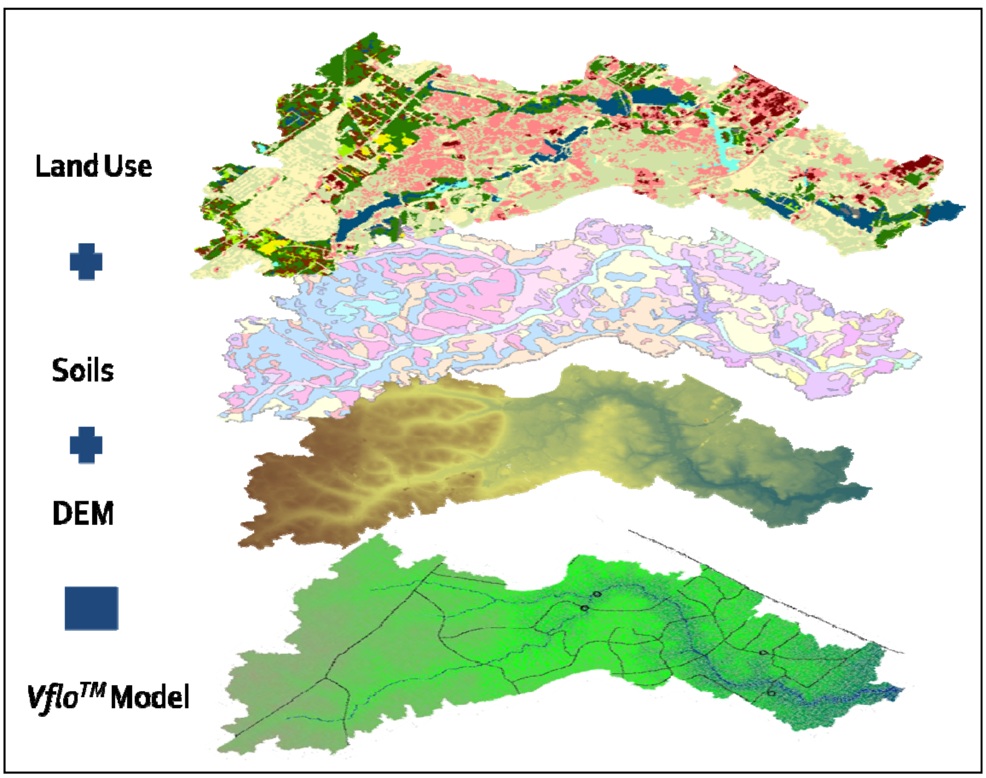


Figure 2-3 Illustration of preprocessed inputs that go into *Vflo*^{TM} model

The Woodlands watershed contains two reservoirs, Bear Branch Reservoir and Lake Woodlands, which were built into the model. Figure 2-4 below is an image of the spillway at Bear Branch Reservoir. These reservoirs help retain some flood water, discharging it downstream in a more controllable manner. Dimensions of the reservoirs and spillways were measured in order to develop rating curves for the *Vflo*^{TM} model

Figure 2-4 Image of the spillway at Bear Branch Reservoir

A reservoir is modeled by *Vflo*^{TM} with a storage-elevation curve and a discharge-elevation curve to route water through the reservoir. This information was not available for the two reservoirs and was calculated by hand for this research. The spillway equation (Eq. 2-1) was used to calculate the discharge-elevation curve, and GIS calculations were used to create the storage-elevation relationships.

Equation 2-1

$$Q = \frac{2}{3} Cb\sqrt{2g}\ H^{(3/2)}$$

The resulting storage-elevation and discharge-elevation curves for Bear Branch Reservoir Figure 2-4 were imported into *Vflo™* as shown in Figure 2-5.

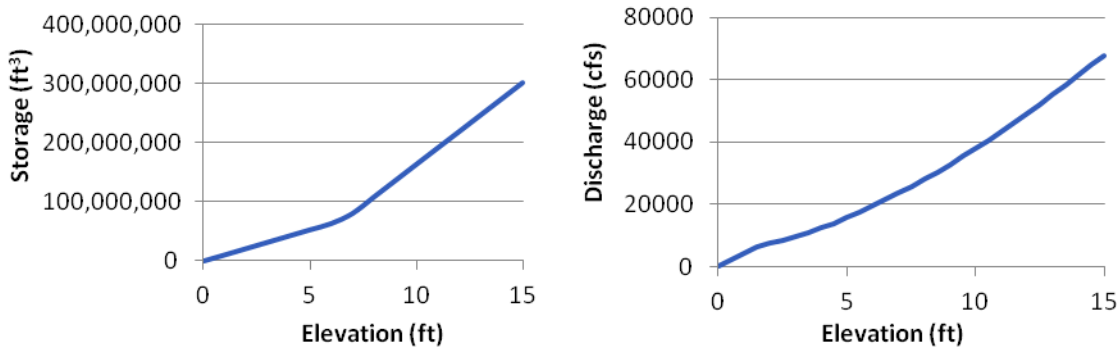


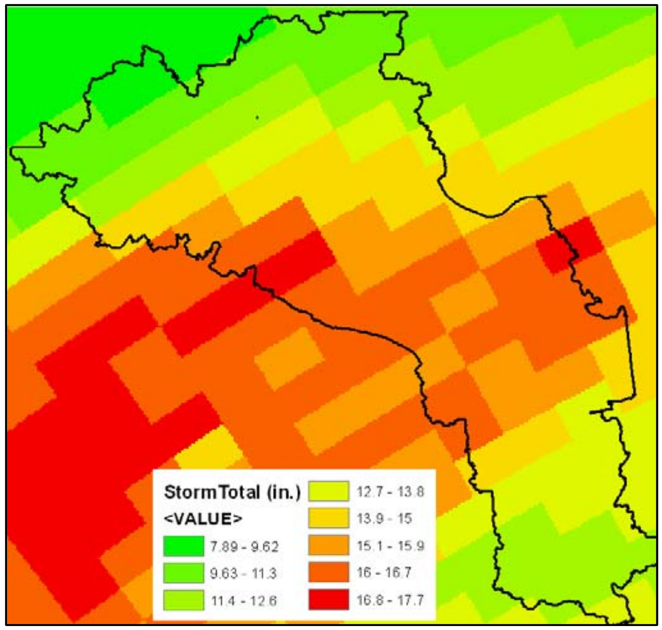
Figure 2-5 Rating curves for Bear Branch Reservoir.

The data imported into the model up to this point is representative of The Woodlands in its most recent state of development. 2006 land cover data was the most currently available data for land use and imperviousness of the watershed. This model is referred to as 2006 development and is assumed to closely represent today's development conditions. In order to represent different development scenarios, this model was adjusted and will be discussed later in this chapter.

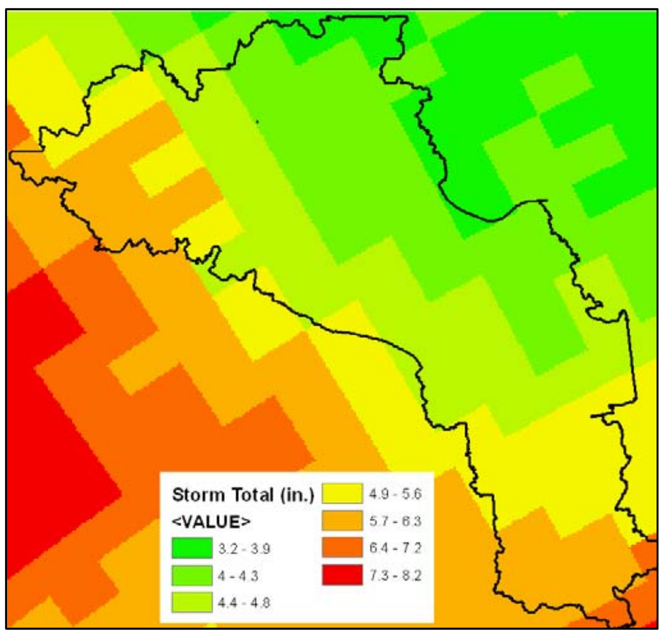
2.3 Model Calibration

The 2006 development model was calibrated to two storm events with NEXRAD radar rainfall. Radar rainfall was elected for calibration because of its ability to capture the variability of intensity in Gulf Coast storms, which rain gage data may fail to capture. Observed streamflow data was obtained from the USGS National Water information System for the gage 08058450, which is on Panther Branch where it crosses Sawdust Rd (USGS, 2012). Observed hydrographs from this stream gage were used to calibrate the model.

The two storm events chosen for calibration were Hurricane Ike in 2008 and an intense storm event in April 2009. NEXRAD data was collected by the national Weather Service in Dickinson, Texas, and was processed by Vieux and Associates. Hurricane Ike delivered 13.8 inches of rain to The Woodlands within a 37 hour period, categorizing the storm as a 50-100 year event. The April 2009 event resulted in about 5 inches of rain within 24 hours, designating it as a 2-5 year storm event (Dodson & Associates & D. A. Vogt Engineering, 1989). Figure 2-6 shows the radar rainfall storm totals over the watershed for the two storms, and Figure 2-7 shows the radar rainfall average hyetograph for the whole watershed. In the hyetopraphs, precipitation is averaged for the entire watershed and is recorded in inches per hour in 10 minute intervals. These two storms caused major flooding throughout the greater Houston area and serve as good storms for hydrologic analysis.

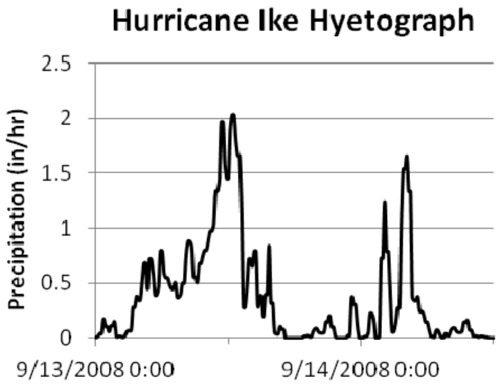


(a)

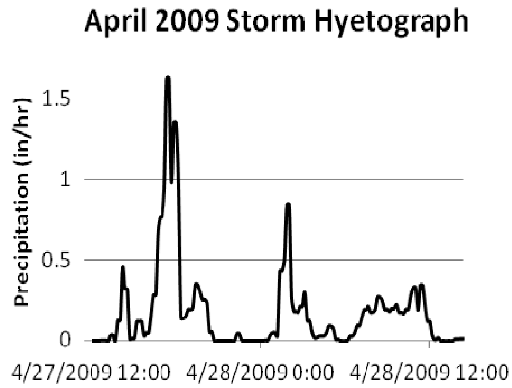


(b)

Figure 2-6 NEXRAD radar rainfall totals for (a) Hurricane Ike and (b) April 2009



(a)



(b)

Figure 2-7 Average rainfall hyetographs for (a) Hurricane Ike and (b) April 2009. Precipitation is recorded in inches per hour in 10 minute intervals.

Calibration of a *Vflo*^{TM} model is done through the use of calibration factor scales to match observed streamflow hydrographs to the modeled hydrographs. The calibration factors allow adjustment of the model parameters for individual cells or a group of cells within the model by multiplying each cell's parameter by the calibration factor.

The calibration process involved a trial and error method, primarily adjusting channel roughness, overland flow roughness, initial saturation, and hydraulic conductivity. Each parameter had a different effect on the downstream discharge hydrograph. The first parameter adjusted was the channel roughness, which had a significant effect on timing and peak flow. Overland roughness was adjusted next, to further capture the timing and peak of the observed hydrograph. Lastly, hydraulic conductivity and initial saturation were adjusted based on antecedent rainfall amounts. Understanding of the physical system must be considered when adjusting these parameters, because the resulting parameter values must remain representative of what is being modeled in the field. The modeled hydrograph was evaluated against the observed hydrograph with careful attention paid to the volume of outflow, peak flow, and time to peak. This procedure was conducted separately for both rain events.

2.4 Model Development for Undeveloped Watershed

A new *Vflo*^{TM} model was developed to represent The Woodlands watershed in its prior, undeveloped condition. This would allow comparison of hydrologic responses to precipitation before and after construction of The Woodlands community, which aimed to preserve the pre-development hydrology. The elevation data and soil characteristics remained the same as what was in the 2006 development model, assumed to remain unchanged throughout the development time frame. The other parameters, roughness and imperviousness, were adjusted to reflect the watershed in its more natural state.

In order to determine the Manning's roughness value that should be imported into the model, the vegetation type for the natural watershed had to be verified. The 1983 USGS LandSat imagery of the watershed was obtained, revealing the homogeneous Evergreen and Mixed Forest land use type that existed prior to development. A uniform roughness value of 0.094 was initially set for the undeveloped watershed, and the percent impervious cover was set to 0.

2.5 Calibration of the Undeveloped Watershed Model

Historical rainfall and streamflow data for calibration was collected from a water quality study conducted by EPA in the 1970s (Diniz & Espey, 1979). The purpose of the EPA study was to examine methods of maximizing the use of water resources in a planned urban environment, while minimizing their degradation.

The EPA study contained rain gage rainfall data for five events in 1974 and corresponding streamflow hydrographs at Sawdust Rd. The location of each rain gage was unknown, therefore, an averaged hyetograph was used for the precipitation input. Averaged hyetographs and downstream hydrographs from the EPA study are shown in Figures 2-8 and 2-9 (Diniz & Espey, 1979). Calibration of the undeveloped model to these historical rain events required adjustment of the model parameters as described previously.

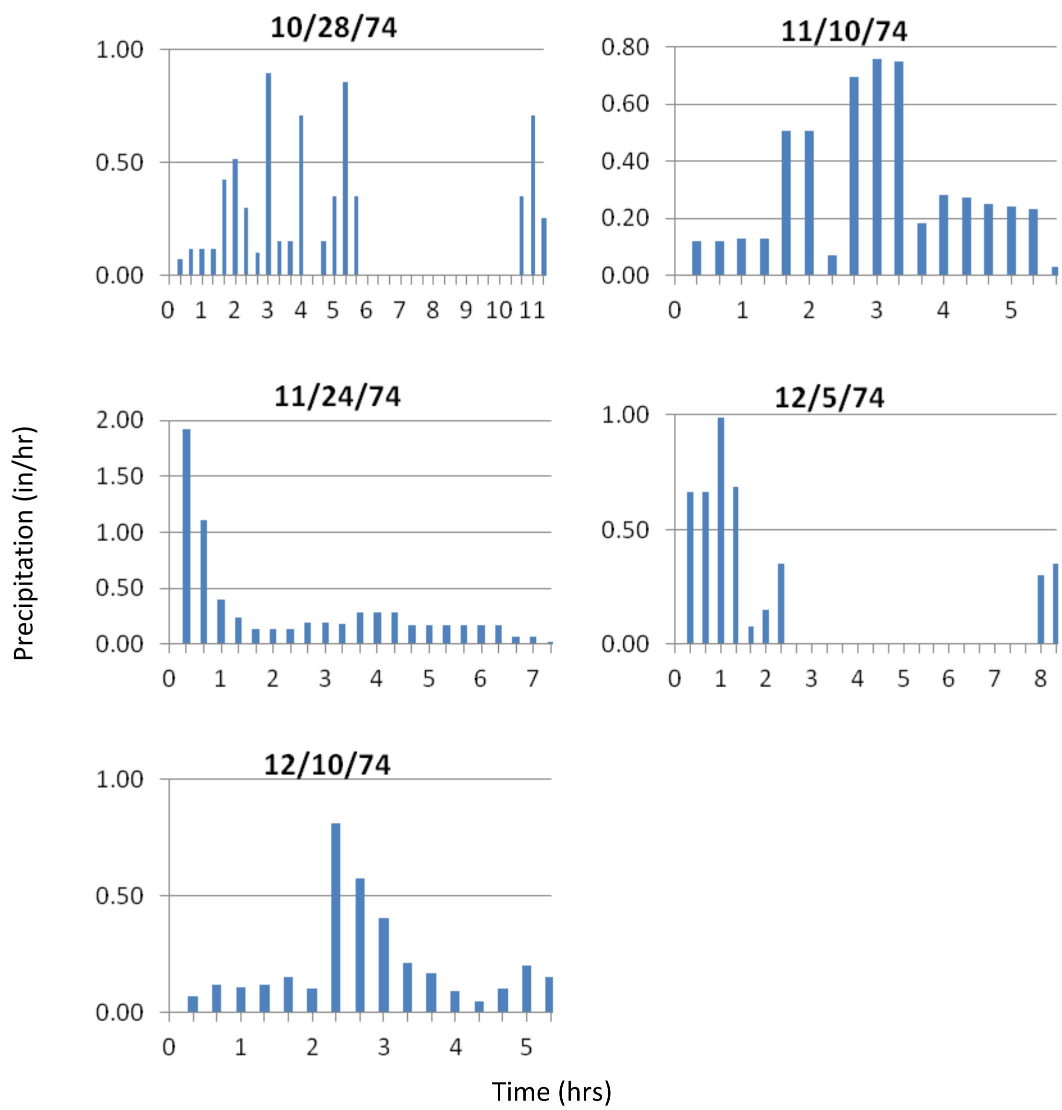


Figure 2-8 Historical rainfall hyetographs for 1974 storms

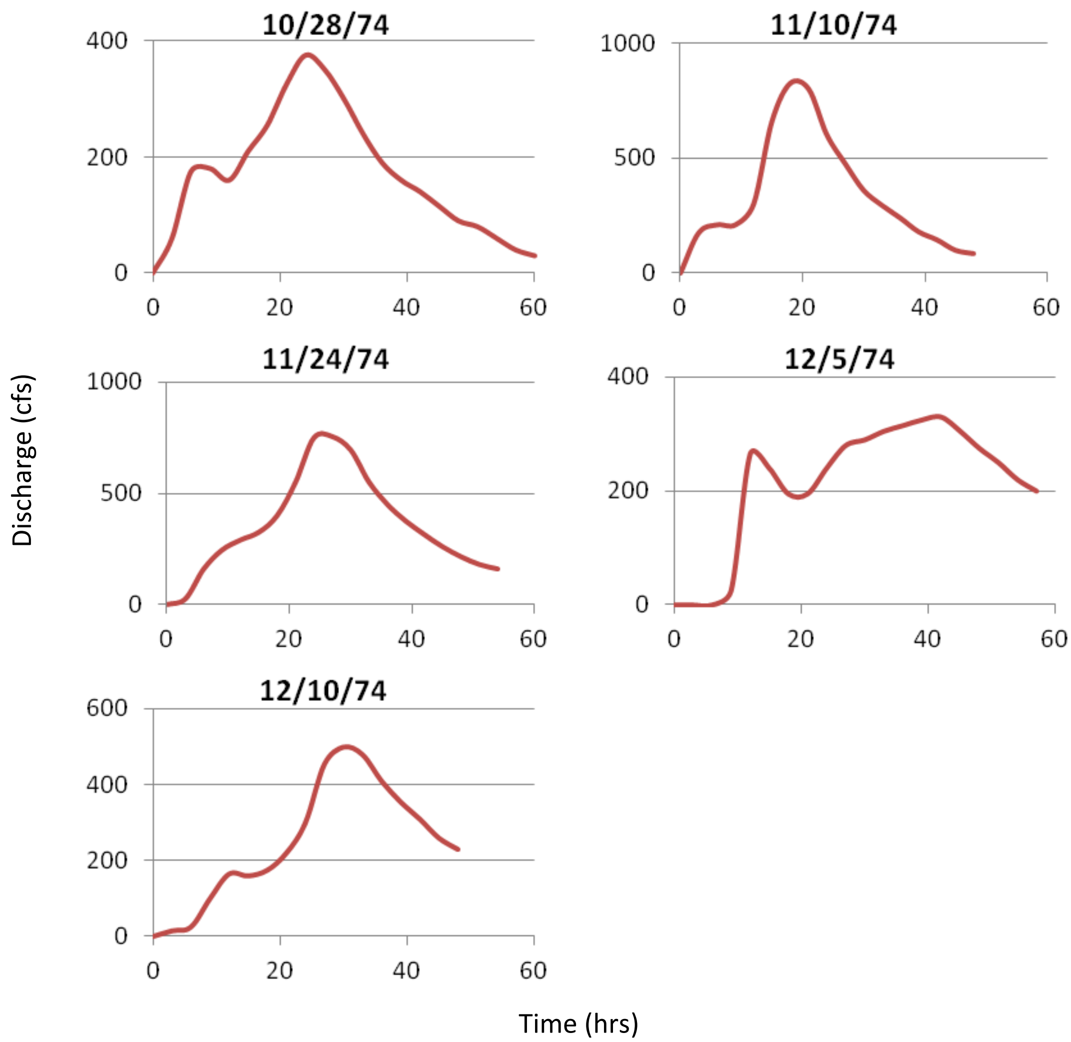


Figure 2-9 Observed streamflow at Sawdust Rd. for 1974 storms

2.6 Model Development for Hypothetical Highly Urbanized Watershed

A third model was created to represent The Woodlands if it had been developed like most of the greater Houston area, i.e. lots of concrete. In order to create this model, the 2006 development model was altered so that it would reflect this hypothetical scenario. Again, the elevation and soils data remained the same as in the 2006 development model, but the land use values were changed.

The overland roughness value and percent imperviousness for this hypothetical watershed were interpreted from an existing calibrated *Vflo*^{TM} model for Cypress Creek (Teague, 2011). The Cypress Creek watershed is a highly urbanizing watershed in the northwest part of Houston, near The Woodlands, that exhibits typical urban development for the Houston area. Parameter values for the lower portion of Cypress Creek, which is fully developed, were averaged and imported into the hypothetical model for The Woodlands. Average imperviousness for this area was determined to be 27% and the average overland roughness value 0.024, in contrast to The Woodlands which has average parameters of 19% and 0.032 respectively. The new parameters were input into the models and the channel cells were assigned a roughness value of 0.015, which is typical for concrete channels. The highly urbanized model was used as a comparison to streamflow from the other models, contrasting the hydrologic response of the watershed to different development scenarios. The different parameters used for each development scenario can be seen in Table 2-3.

Table 2-3 *Vflo*^{TM} land use parameters for development scenarios

	Undeveloped	**2006 Development**	**Intense Development**
Imperviousness	0%	19%	27%
Channel Roughness	0.032	0.026	0.015
Overland Roughness	0.066	0.033	0.024

2.7 Comparing Streamflow from Development Scenarios

Three *Vflo*^{TM} models were created for The Woodlands watershed, each representing a different development scenario. The watershed was modeled in undeveloped conditions, 2006 development conditions, and a hypothetical intense developement condition. Recorded rain events were run in each of the models and predicted streamflows were compared to help evaluate the impact development has on rainfall-runoff responses.

The rain events used in this comparison included historical storms and radar rainfall for Hurricane Ike. When a precipitation input was run in the models, initial saturation and hydraulic conductivity remained the same in each model to ensure consistency. The only parameters that varied among the models were roughness and percent impervious values. After running a storm event in all three models, predicted hydrographs from Sawdust Rd. were analyzed and compared. In particular, changes in volume, peak flow, and time to peak were calculated.

As a final comparison between the three development scenarios, the 100 year design storm was run in the models. The 100 year 24 hour design storm is defined to have a 1% chance of occurring in any given year, and is the design standard for new channels and developments. According to the Tropical Storm Allison Recovery Project (TSARP), the 100 year, 24 hour design storm will produce 12.6 inches of rainfall (TSARP, 2009). This design storm was run in the *Vflo*^{TM} model for each development scenario and compared in the same matter as before.

Vflo^{TM} software allows the user to enter a synthetic design storm using the SCS temporal distribution. The design storm rainfall depth is derived from IDF curves, which is distributed through time according to the region of interest (Bedient, Huber, & Vieux, 2008). The Gulf Coast Region, where The Woodlands is located, has a Type III distribution according to the Natural Resources Conservation Service (NRCS, 1986). Thus the 100 year, 24 hour design storm was entered into *Vflo*^{TM} as a Type III storm with a depth of 12.6 inches and duration of 24 hours.

2.8 Small Sub-Area Predictions

This thesis also investigated the fine scale limits and accuracy of a distributed hydrologic model. The ability to predict a hydrograph for any cell within the watershed is a very unique attribute to the *Vflo*^{TM} software, however, can the model retain its dependability when analyzing small contributing surface areas?

The *Vflo*^{TM} model of The Woodlands 2006 development scenario, calibrated to Hurricane Ike, was used to assess five small sub-areas within the watershed. The areas analyzed range in size from 10 to 100 acres, including two Rural (undeveloped) areas and three Residential areas. Since measured flow data was not available for the outlet of these small sub-areas, the Rational Method was used as a benchmark comparison. A summary of the characteristics of the five sub-areas and Rational Method variables are shown in Table 2-4. To account for the variability of acceptable runoff coefficients, a minimum and a maximum were selected for C from the Montgomery Drainage Criteria Manual (Dodson & Associates & D. A. Vogt Engineering, 1989).

Table 2-4 Rational Method calculation variables for each sub-area.

	Rural 1	Rural 2	Residential A	Residential B	Residential C
Area (ac)	12.8	102.4	89.6	44.8	51.2
Cmin	0.15	0.15	0.32	0.32	0.32
Cmax	0.25	0.25	0.5	0.5	0.5
Drain Length (ft)	1466	3641	4007	2121	2508
velocity (ft/s)	0.5	0.5	2.5	2.5	2.5
i 10 yr (in/hr)	3.82	2.04	4.58	5.90	5.56
i 100 yr (in/hr)	5.19	2.89	6.16	7.79	7.38
Tc (min)	48.9	121.4	36.7	24.1	26.7

Guidance from the Montgomery County Drainage Criteria Manual was used for Rational Method calculations and assumptions (Dodson & Associates & D. A. Vogt Engineering, 1989). Rational procedures were followed to calculate the Tc and rain intensity for the 10 year and 100 year design storms in each sub-area. Runoff from these areas was considered non-channelized flow, and the figure in Appendix A from the Fort Bend County Drainage Criteria Manual was used to estimate the runoff velocity in each sub-area (Fort Bend County Drainage District, 2011). Additionally, to compensate for the travel time from house lots to streets, ten minutes was added to the Tc calculation in residential areas.

The rainfall intensity calculated in the Rational Method was then applied to the *Vflo*^{TM} model for a duration equal to the calculated Tc. Peak discharge predicted by both methods was analyzed and compared.

The Rational Method equation contains three variables that could possibly explain inconsistency between the methods. The Area was undoubtedly a constant variable for each sub-area, and could not be the cause for any variance. The second variable, I, is determined from the area's time of concentration. To check congruency of this variable, which would weaken the comparison if they were drastically different, the time of concentration for each method was compared. Lastly, the runoff coefficient was the third variable that may cause any differences in peak flow predictions. The coefficient used in the Rational Method cannot be directly compared to *Vflo*^{TM} because *Vflo*^{TM} calculates infiltration through Green-Ampt and uses Manning's equation to calculate runoff. In order to overcome this difference in methodology, a range of acceptable runoff coefficients was used for the Rational calculations.

3 Results

3.1 Calibration Results

Rainfall data was used to model the rainfall-runoff process in The Woodlands watershed for seven storm events. The hydrologic model, *Vflo*^{TM}, was evaluated at Sawdust Rd. and compared against measured streamflow data from USGS gage 08068450. Overall the model simulated hydrology of the watershed at an acceptable level, matching well with the observed streamflow peaks, outflow volume, and timing.

3.1.1 Hurricane Ike

The 2006 development model with Hurricane Ike precipitation matched the measured hydrograph at Sawdust Rd. very well. A comparison of the modeled versus observed streamflow is shown in Figure 3-1. The preceding months leading up to this storm event were very dry, thus in order to calibrate the model for this storm event the initial saturation was significantly reduced. Averaged across the watershed, the average initial saturation for the soils was 9% and the average hydraulic conductivity was 2.12 in/hr. The other parameters in the model adjusted for this storm event were the Manning's roughness values for channel cells and overland cells. The calibration efforts produced an average channel roughness value of 0.026 and an average overland roughness value of .038. These roughness values are appropriate for the vegetation type and channel characteristics of the watershed, and were used for further calibration efforts.

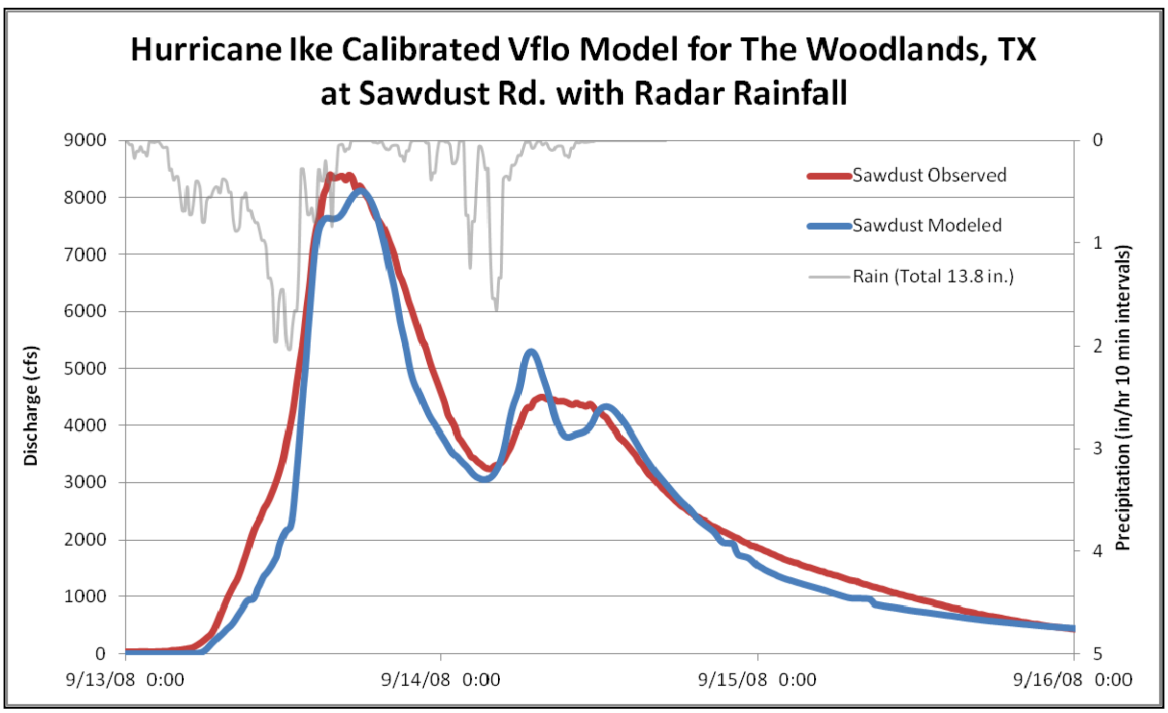


Figure 3-1 Modeled and observed stream flow hydrographs for Hurricane Ike at Sawdust Rd.

The agreement between modeled and observed streamflow can be seen in the figure above. All three characteristics of the hydrographs analyzed, matched very well. The modeled peak flow was only 3% less than the observed peak flow, and exhibited only a 4% difference in volume. In addition, the difference in time to peak between modeled and observed was 2.3 hours.

3.1.2 April 2009 Storm

The model with April 2009 precipitation was unable match as well to the measured hydrograph at Sawdust Rd. A graph comparison of the modeled versus observed streamflow is shown in Figure 3-2. Calibration to this event was not easily accomplished. Attempting to calibrate to a hydrograph with a triple peak, as seen here, is very challenging in and of itself.

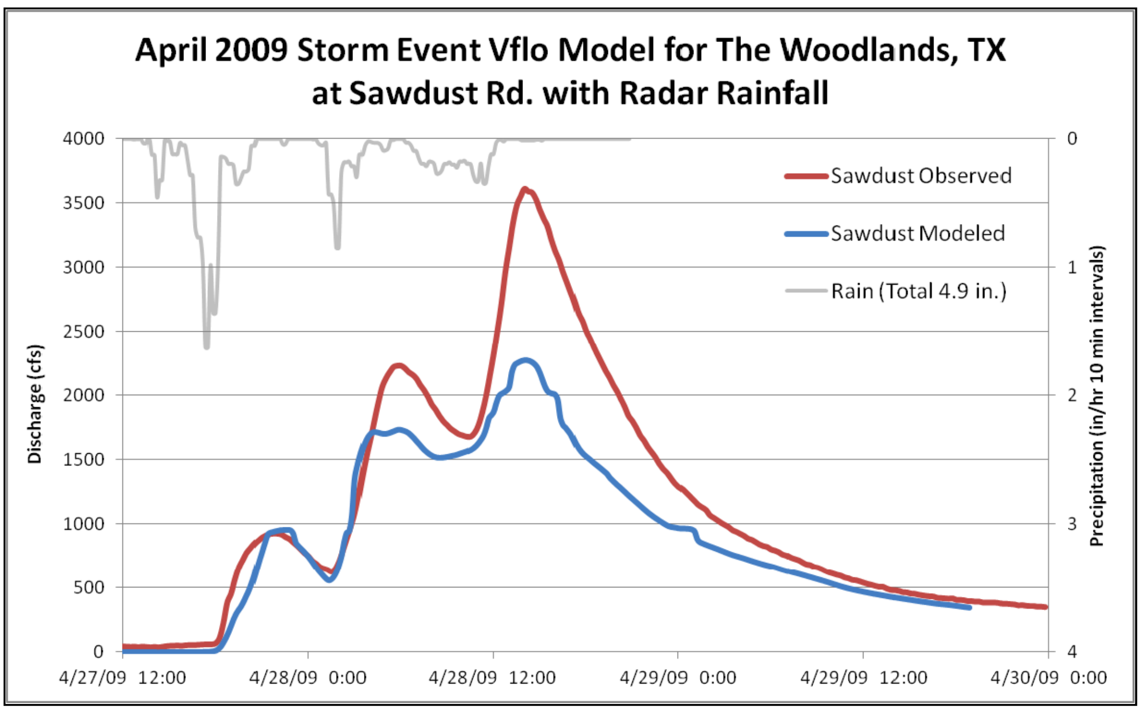


Figure 3-2 Modeled and observed stream flow hydrographs for April 2009 event at Sawdust Rd.

The preceding time period leading up to this storm included much more rainfall, requiring the initial saturation and hydraulic conductivity be adjusted accordingly. The average initial saturation for the watershed was 54% and the average hydraulic conductivity was 1.41 in/hr.

The April 2009 storm event proved very difficult to calibrate to. However, the timing of the model matched to that of the observed flow for all three peaks. In fact, the difference in time to peak for both hydrographs was 0 hours. The first peak matched well, and the rising limb of the second peak matched well, but a discontinuity between the two graphs arised towards the latter part of the storm. Overall, the difference in peak flow was 37% and the difference in volume was 16%.

To further investigate the disagreement between modeled streamflow and observed streamflow, the April 2009 rain event was run in the model with 100% saturation. The purpose of doing this was to test the validity of the radar rainfall for the event, which was adjusted to local rain gage measurements. The modeled streamflow hydrograph with no losses is compared against observed streamflow in Figure 3-3. The third peak of the streamflow is still underestimated by the model, even when all precipitation is converted into runoff. This leads to the conclusion that the radar rainfall data for this event does not accurately represent the entirety of the storm. Spring storm events in the Gulf Coast region, such as this one, can have isolated areas of intense rainfall, which not be captured by sparse rain gages. Since the NEXRAD radar rainfall is adjusted to rain gage data, it is possible for inaccurate rain gage data to render the radar inaccurate as well. The April 2009 storm event was no longer used for analysis in this research.

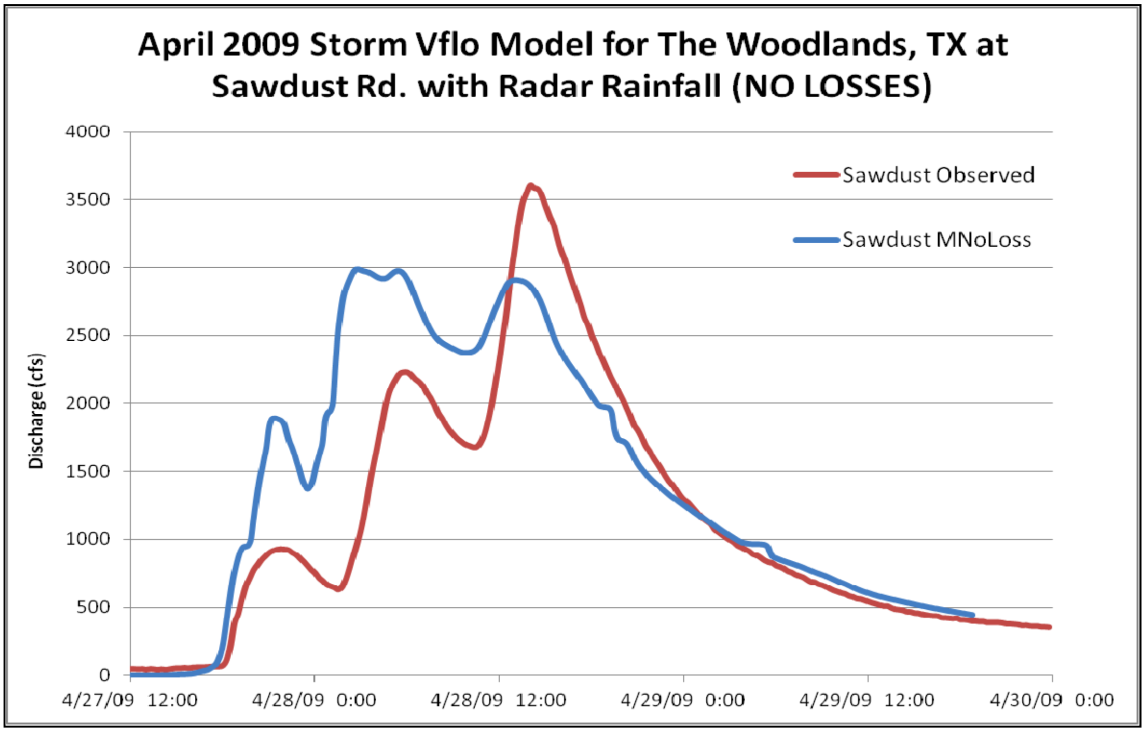


Figure 3-3 Modeled hydrograph with zero losses and observed streamflow hydrograph for April 2009 at Sawdust Rd.

3.1.3 Historical Storms

Calibration of the undeveloped model to the streamflow of historical storm events from 1974 was successful. A comparison of modeled versus observed streamflow for the historical storms is shown in Figure 3-4. The calibration was deemed acceptable considering the rough rainfall data available from the 1979 EPA report.

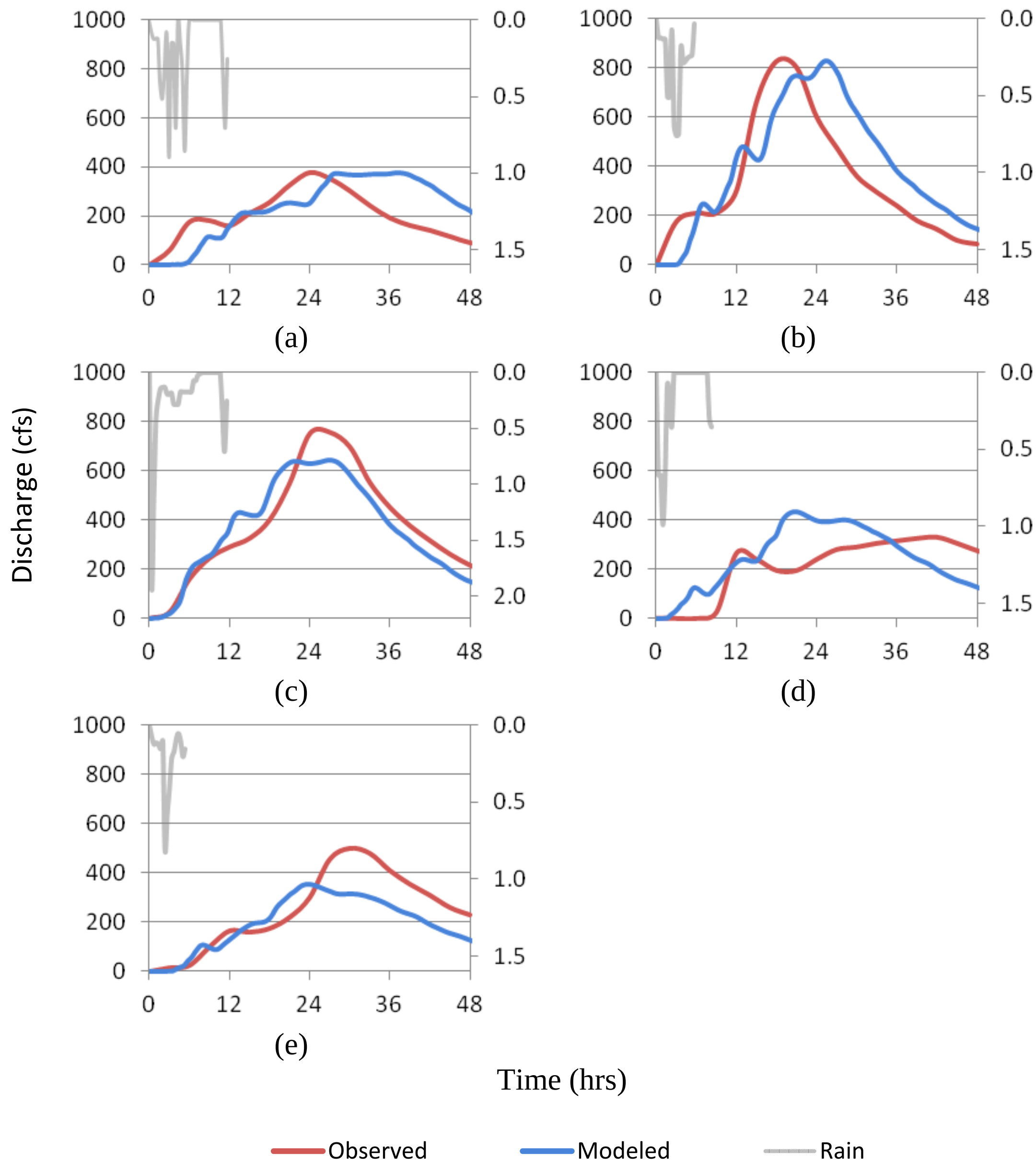


Figure 3-4 Modeled streamflow and observed streamflow hydrographs for historical storms: (a) 10/28/74 (b) 11/10/74 (c) 11/24/74 (d) 12/5/74 (e) 12/10/74 at Sawdust Rd.

Overall, the volume of observed streamflow and modeled streamflow matched very well and differed by an average of 14%. The calibrated roughness values for channel cells (0.032) and overland cells (0.066) in the undeveloped model effectively mimicked the hydrology of the watershed in its prior, natural state. With a calibrated model of the undeveloped watershed, a calibrated model of the 2006 development, and a hypothetical model of intense development, the rainfall-runoff response of the watershed to storm events with different development scenarios can begin to be analyzed.

3.2 Development Comparisons

The models representing The Woodlands in its three stages of development (undeveloped, 2006 development, and highly urbanized) were used to analyze and compare streamflow from the historical storm events and Hurricane Ike. Streamflow was analyzed for each storm event at Sawdust Rd.

3.2.1 Historical Storms

The historical storms were first modeled with undeveloped and 2006 development conditions, using 1974 precipitation from October 28, November 10, and November 24. These three storms were selected for further analysis due to their good match during the calibration step, and for the purpose of time efficiency. Ideally, the predicted 2006 development hydrograph would correlate very well with the observed streamflows in 1974, showing unaffected hydrology during the course of development. Again, this was an objective of The Woodlands development. The comparison of modeled versus observed streamflow for these three events is shown in Figure 3-5.

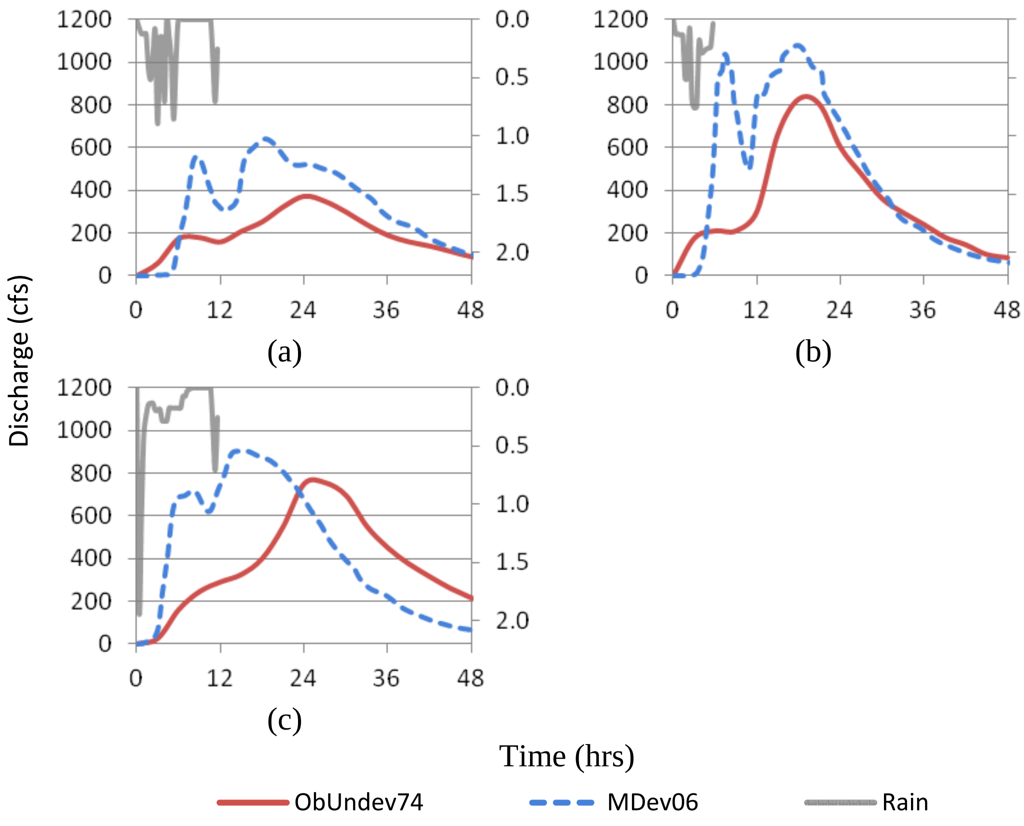


Figure 3-5 Modeled 2006 development hydrographs vs. observed historical streamflows for (a) 10/28/74 (b) 11/10/74 (c) 11/24/74 at Sawdust Rd.

The predicted peak flow and timing of streamflow for these events is different for the modeled 2006 development compared to what was observed in 1974. However, the peak flow increased about 100 to 200 cfs above the historical observed peak flow, which is not a major increase. Averaged across all of the historical storms, the peak flow increased about 15% above the observed peak. The timing of the 2006 development model hydrographs also shifted earlier in time.

On average, for the historical storms, the 2006 development model predicted a shift in time to peak of 10 hours, which is likely due to some modification of the natural watershed during development. Natural drainage corridors were protected as best as possible during the design of The Woodlands, but some channelization and drainage networks were required.

Next, the historical precipitation was run in the hypothetical model of a highly urbanized watershed. A comparison of modeled versus observed streamflow for the historical storms in a highly urbanized watershed is shown in Figure 3-6.

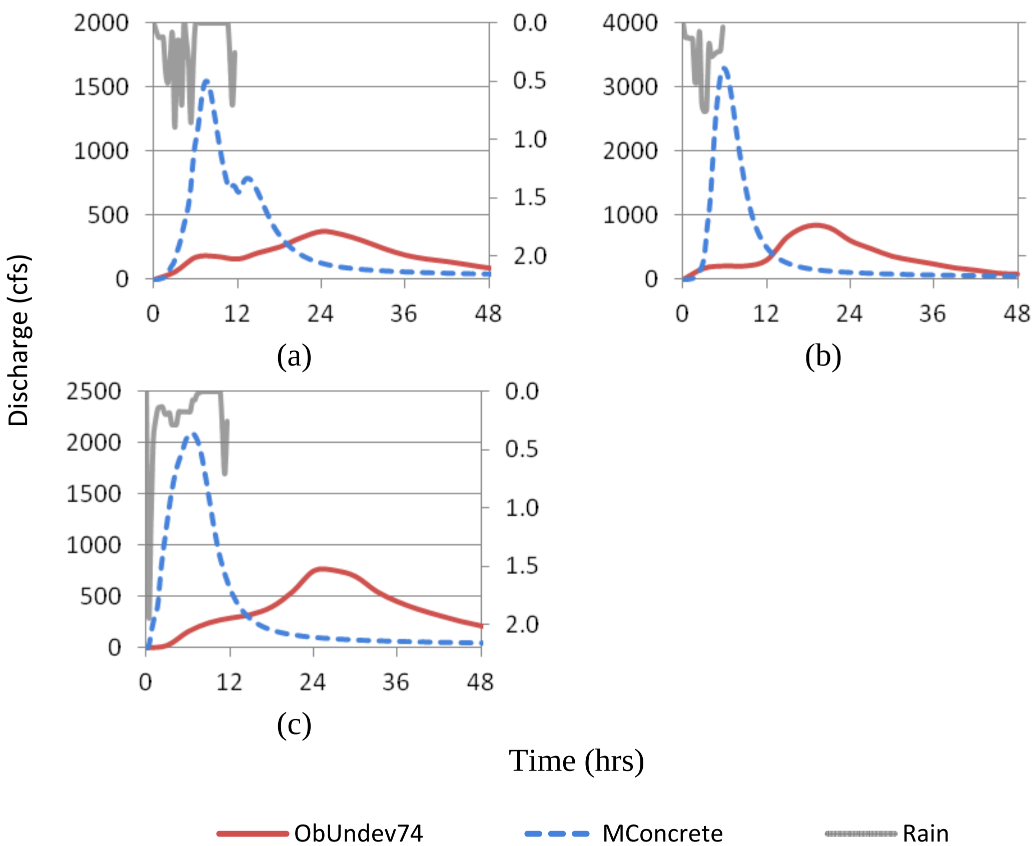


Figure 3-6 Modeled highly urbanized hydrograph vs. observed historical streamflows for (a) 10/28/74 (b) 11/10/74 (c) 11/24/74 at Sawdust Rd.

The streamflows predicted by the hypothetical model are drastically different than the observed flows. The peak flows are nearly three times the observed flows, and the time to peak is almost a full day earlier. In more definite terms, the peak flow increased by an average of 263% and the time to peak shifted on average 15 hours earlier. As expected from a watershed laden with impervious cover and concrete channels, the hypothetical model effectively illustrates how the hydrology of The Woodlands would be different if it was developed like much of the surrounding Houston areas.

3.2.2 Hurricane Ike

Next, radar rainfall for Hurricane Ike was run in the undeveloped and hypothetical development models to analyze the impact of development during a much more severe storm event. In this case, the observed data came from 2008 and was used as the basis for comparing undeveloped and highly developed conditions. Figure 3-7 illustrates how the undeveloped The Woodlands watershed may have responded to Hurricane Ike.

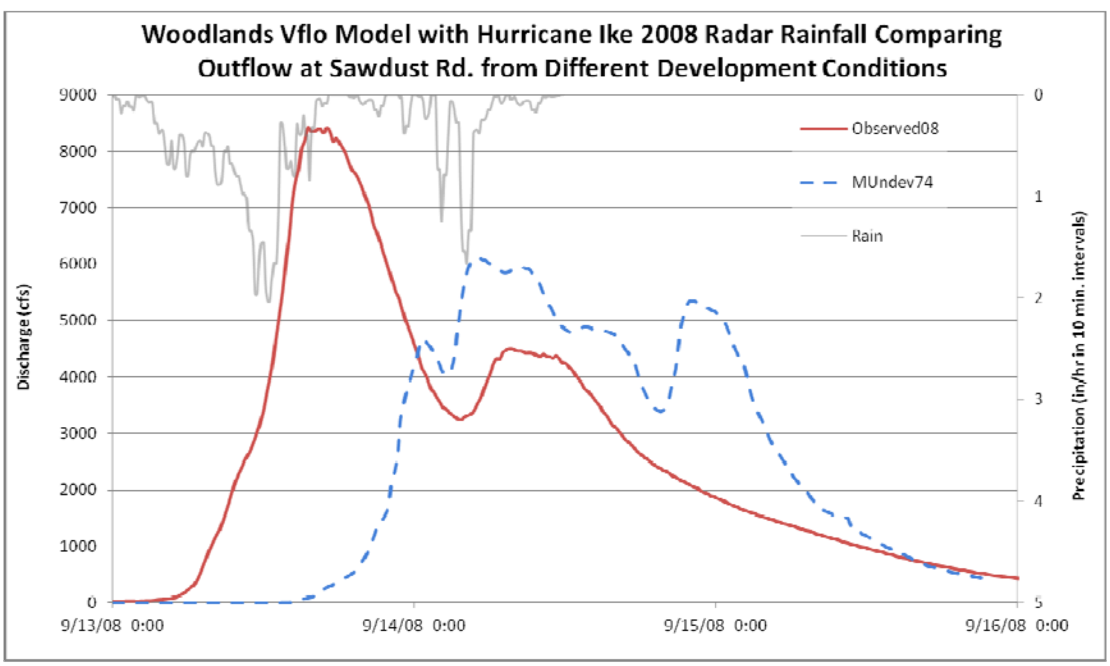


Figure 3-7 Observed hydrograph for Hurricane Ike vs. modeled undeveloped hydrograph at Sawdust Rd.

From the figure above, it can been seen that the undeveloped model predicted stream flow at Sawdust Rd. for Hurricane Ike to have a smaller peak and a later time to peak. The predicted peak flow was 27% less than what was observed in 2008, and the peak was predicted to occur 13.5 hours later. Considering that this was a 50-100 year storm event, the model suggests that the Development of The Woodlands has not had a significant impact on the natural hydrology of the watershed.

Next, Hurricane Ike rainfall was run in the hypothetical development model to evaluate the possible impacts this storm could have had on the The Woodlands if it had been intensely developed. Figure 3-8 shows the comparison of observed streamflow and modeled streamflow in the highly urbanized scenario.

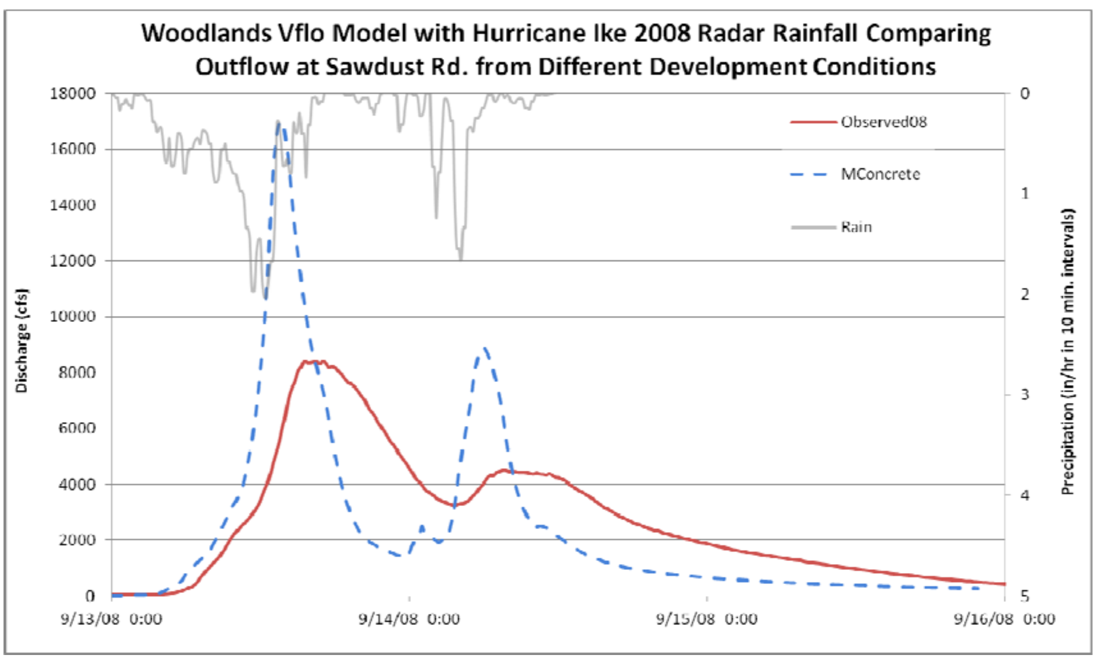


Figure 3-8 Observed hydrograph for Hurricane Ike vs. modeled highly urbanized hydrograph at Sawdust Rd.

The highly urbanized watershed responds more rapidly to Hurricane Ike in the model. The rising limb and falling limb of the modeled hydrograph are much steeper as a result of the runoff racing out of the watershed without impediment. The peak flow modeled for the highly urbanized watershed is 102% higher than what was observed in 2008 with The Woodlands development in place. When compared to the prediction of the undeveloped model, the highly urbanized peak flow increased 178% than what would occur in the watershed with no development. As a final comparison between the three development scenarios, the 100 year design storm was run in the models.

3.2.3 100 Year Design Storm

The results of the 100 Year design storm comparison shows that The Woodlands drainage design effectively protects the development from major storm events. Figure 3-9 illustrates the difference in 100 year stream flow for the three development scenarios.

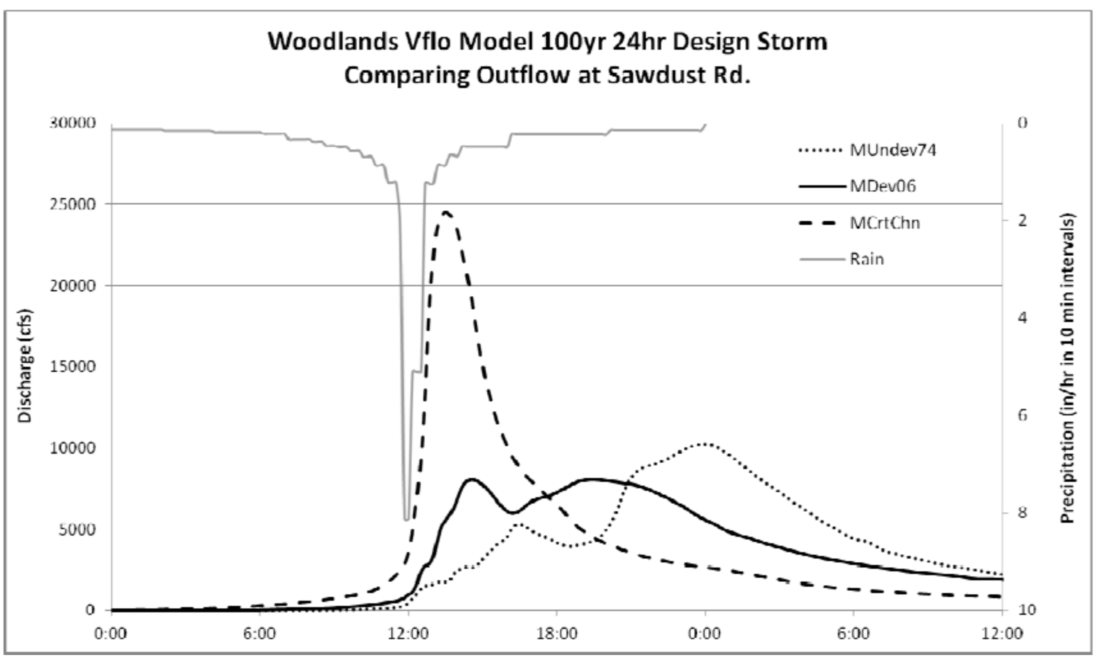


Figure 3-9 Comparison of hydrographs for the 100 year design storm in the undeveloped, 2006 development, and hypothetical development scenarios.

As seen in the above figure, the natural drainage system and the two reservoirs actually reduce the 100 year peak flow by about 20%. The reservoirs effectively alleviate the peak flows. In fact, if The Woodlands was developed with the natural drainage system only and no reservoirs, the *Vflo*^{TM} model predicted a peak flow of 14,200 cfs, which is 38% higher than the predicted peak flow in the undeveloped model. The hypothetical development model shows a 200% increase in peak flow over the 2006 development model peak flow. These results show the success of The Woodlands drainage design in maintaining the pre-existing hydrology of the watershed.

The design of The Woodlands is able to effectively manage major storm events on site, minimizing flood damage to the community and downstream. Table 3-1 summarizes the changes in peak flow among the three development scenarios for all storm events analyzed.

Table 3-1 Peak flow (cfs) comparisons for development scenarios

	Undeveloped	**2006 Development (% diff.)**	**Intense Development (% diff.)**
10/28/1974	375	573 (53%)	1,543 (312%)
11/10/1974	825	952 (15%)	3,301 (300%)
11/24/1974	755	807 (7%)	2,102 (178%)
12/10/1974	500	491 (2%)	-
Hurricane Ike	6,112	8,119 (33%)	17,017 (178%)
100 yr. Storm	10,270	8,106 (-21%)	24,516 (139%)
Avg. Diff.	-	**15%**	**221%**

Not only were the discharge rates in the watershed analyzed, the difference in timing of the hydrographs were evaluated as well. The figures above illustrate how as the watershed progresses from undeveloped to highly developed, generally the time to peak of the hydrograph diminishes. The shift in timing of the 2006 development compared to the undeveloped watershed can be contributed to some drainage improvements and inevitable construction of impervious surfaces. Table 3-2 summarizes the change in time to peak among the three development scenarios.

Table 3-2 Time to Peak Comparisons (hrs) for development scenarios

	Undeveloped	2006 Development (Δ hrs)	Intense Development (Δ hrs)
10/28/1974	20	14.67 (5)	7.5 (12.5)
11/10/1974	15	5.0 (10)	2.8 (12)
11/24/1974	26	13.3 (13)	5.5 (21)
12/10/1974	27.3	5.33 (22)	-
Hurricane Ike	16.8	5.66 (11)	1.5 (15)
100 yr. Storm	24	19.5 (4.5)	13.5 (10.5)
Avg. Diff.	-	**10.9 hrs**	**14.2 hrs**

Hurricane Ike caused some minor flooding of roadways in The Woodlands, which they were designed for, but very little damage was caused to building structures. Imagine a highly urbanized watershed with double the amount of runoff traveling downstream in a short period of time, as predicted by the hypothetical model. This would most likely cause significant damage to the watershed and structures within it, and would have an impact on areas further downstream.

3.3 Small Sub-Area Analysis

The *Vflo*^{TM} model for The Woodlands watershed, calibrated to Hurricane Ike, was used to analyze peak discharge from five small subareas within the watershed. Since measured data for these small areas was unavailable, the Rational Method was used as a benchmark comparison. Disparity between these two methods was minimized as much as possible to allow fair comparison between the predicted discharges.

The three variables in the Rational Method equation were examined to avoid inconsistent predictions between the two methods. The Area was constant for each sub-area. The second variable examined, Time of Concentration, is used to determine the rain intensity in the Rational equation. The Rational Method equilibrium time (Tc) was compared to the Tc of each sub-area in *Vflo*^{TM} as shown in Table 3-2.

Table 3-3 Time of Concentrations for Rational Method and *Vflo*^{TM}

	Rural 1	**Rural 2**	**Residential A**	**Residential B**	**Residential C**
Rational Tc (min)	48.9	121.4	36.7	24.1	26.7
Vflo^{TM} Tc (min)	60	110	40	30	30

Vflo^{TM} does not explicitly give the time of concentration, so the hydrographs were forced to equilibrium. By imputing a constant rain intensity for a sufficiently long duration, the hydrograph will eventually flatten out and allow an estimation of the TC. The third variable in the Rational Method was incorporated as a range of acceptable values. The range of runoff coefficients helps to further minimize any possible discrepancies between the two methods, helping justify their comparison in this analysis.

Peak flows at the outlet of each sub-area were predicted for the 10 year and the 100 year storm event. The results are summarized in Table 3-3, where Q1 is the minimum discharge from the Rational Method using the minimum runoff coefficient; Q2 is the maximum. Results are presented in cfs per acre for analysis and ease of comparison. In general, the *Vflo*^{TM} model predicted a higher peak discharge than the Rational Method computation. This analysis, however, can neither prove nor disprove either method, not is it the intention of this analysis.

Table 3-4 Predicted peak flow discharges from Rational Method and *Vflo*^{TM}.

	Rural 1	**Rural 2**	**Residential A**	**Residential B**	**Residential C**
Q1 10 yr (cfs/ac)	0.58	0.31	1.48	1.90	1.79
Q2 10 yr (cfs/ac)	0.96	0.52	2.31	2.97	2.8
Vflo Q 10 yr (cfs/ac)	1.33	0.29	2.40	3.08	2.28
Q1 100 yr (cfs/ac)	0.98	0.55	2.48	3.14	2.97
Q2 100 yr (cfs/ac)	1.63	0.91	3.88	4.91	4.65
Vflo Q 100 yr (cfs/ac)	2.81	0.98	3.88	4.91	3.99

Overall, the results from both methods predicted a reasonable discharge per acre for most of the selected areas. Typical discharge rates for a 100 year storm in this region are expected to be between 0.125 and 1.0 cfs per acre for rural areas, and between 3.0 - 5.0 cfs per acre for residential areas (Harris County Flood Control District, 2010; Fort Bend County Drainage District, 2011; Dunbar, 2012). One exception was observed in the Rural 1 area, where *Vflo*^{TM} predicted a discharge rate greater than what was anticipated. Upon further investigation, the Manning's roughness value for this small rural area was 0.045. This is lower than typical roughness values for undeveloped areas, which typically would be closer to 0.1. This could possibly be attributed to the calibration process of this model.

Remember, the *Vflo*^{TM} model was calibrated for Hurricane Ike, using measured streamflow data near the outlet. It is possible that in this case, the small size of the sub-area (10 ac.) surpasses the limits of *Vflo*^{TM} to accurately predict the discharge. Larger sub-areas appear to be more capable of alleviating discrepancies between actual land use characteristics and modeled parameter values. The roughness value for the Rural 2 area was an average of 0.65, which may have been enough to predict more acceptable flows. Calibration with two or three storms gives more validity to the model, and may contribute to why the roughness value for Rural 1 was low in this case.

The Rural 1 area roughness value was changed to 0.09 in *Vflo*^{TM} to assess the new predicted outflow with the 100 year rain intensity. This increase in roughness value reduced the predicted peak flow, resulting in a discharge rate of 1.88 cfs per acre. This rate is still higher than what is considered typical for undeveloped areas, but it is more reasonable than the discharge originally predicted.

4 Conclusions and Future Work

4.1 Conclusions

This study established two calibrated, fully distributed hydrologic model of The Woodlands, TX watershed in its undeveloped and current development conditions, as well as creating a hypothetical development model. These three models allowed for comparison of rainfall-runoff responses of the watershed with different development conditions consisting of various imperviousness and land cover. The Woodlands watershed was selected because of the development's pioneering master plan approach, especially in regard to its drainage design. George Mitchell's vision for The Woodlands was innovative at the time and has laid the foundation for what is now deemed Low Impact Development.

One of the major objectives of The Woodlands development was to preserve the existing hydrology of the watershed through preservation natural vegetation and drainage corridors. The predominant purpose of this thesis was to assess the success of the development design in achieving this goal. Historical rainfall and a recent major storm event were used to compare peak flows, discharge volume, and time to peak of the responding watershed. Results show that compared to pre-development conditions, the construction of The Woodlands resulted in an average increase in peak flows of only 15% for the small historical storms and only 27% for a major event. Results also show an earlier shift in the time to peak flow. When compared to other urban developments in the Houston area, peak flows are often two to three times greater than pre-development flows. When analyzing a 100 year design storm event, the 2006 development model predicted a lower peak flow than the undeveloped model. This 100 year event included a short period of rainfall with a higher intensity than Hurricane Ike, which resulted in a greater peak flow for the undeveloped model. In the 2006 development model, the peak flow of the 100 year event was successfully attenuated, which can be attributed to the LID practices. These results suggest that the design of The Woodlands effectively protects the development from the 1% occurrence storm event.

The planning and design of a more natural drainage system was elementary at the time, and is significantly better than the alternative investigated in this study. If The Woodlands watershed had been designed like much of the nearby developments, peak flows from the watershed would have been two to three *times* greater than they were prior to development. With all things considered, this study demonstrates the tremendous success of The Woodlands development in preserving the pre-existing hydrology of the watershed while creating a better community for human existence.

The second part of this study employed a calibrated *Vflo*^{TM} model of The Woodlands watershed to analyze the fine scale limitations of the software. The *Vflo*^{TM} model allows use of high resolution elevation, soils, and land use data, which in theory can help the model better predict infiltration and runoff processes. Also, the unique ability of the software to predict hydrographs from any cell within the watershed allowed evaluation of sub-areas in this study on the order of 10 – 100 acres. Five sub-areas were selected within the watershed and analyzed for the 10 and 100 year rain events. To assess the validity of the *Vflo*^{TM} model predictions, peak flows were compared to the highly accepted Rational Method calculations.

Results from this comparison show that the *Vflo*^{TM} model predicted slightly higher peak flows than calculated by the Rational Method, but are generally still within reason.

Further calibration of the model may result peak flows that are more representative of actual discharges by adjusting overland roughness values in some areas; however, this was not feasible during this research. An advantage of using the *Vflo*^{TM} model instead of the Rational Method approach is that it removes some of the assumptions and human judgment, primarily when choosing a runoff coefficient for Rational Method calculations. This coefficient is supposed to represent relief, soil infiltration, vegetation cover, and drainage surface characteristics, which is difficult to capture with a single value. In addition, this single value is calculated to represent the whole drainage area; whereas the *Vflo*^{TM} model uses detailed raster data and accounts for spatial variability within the drainage area.

This thesis suggests that the *Vflo*^{TM} model can be used to predict stormwater discharge from areas within a watershed as small as 10 acres, in replace of more traditional methods such as the Rational Method. The accuracy and high resolution capabilities of distributed hydrologic models should be used by developers and urban planners to analyze various LID and stormwater best management practices. Further research and validation of these results with measured data should be conducted first.

4.2 Future Work

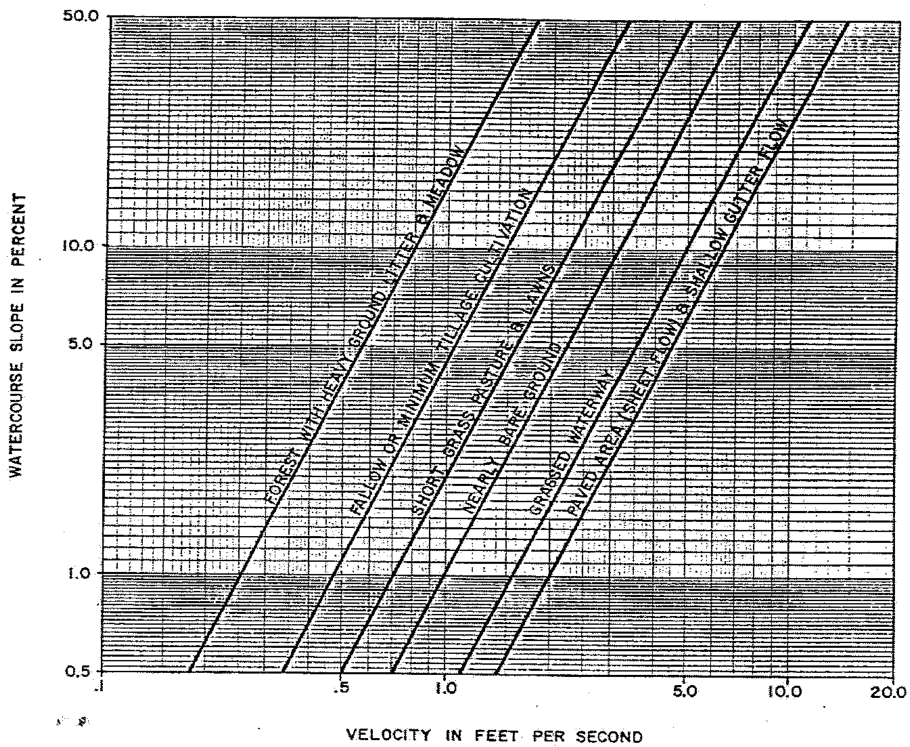
The field of hydrologic modeling is rapidly changing, especially with the advancement in computer processing and GIS data availability. To avoid unnecessary computations, and to help improve the accuracy of runoff predictions, it is important to evaluate the limits of such software. High resolution raster data is not necessary for modeling if more accurate results are not obtained. In addition, how reliable can distributed hydrologic models be when predicting runoff from small areas within a watershed? An accurate fine scale, high resolution distributed model can help evaluate LID practices, giving them more conviction in the eyes of developers.

The Woodlands development, with its innovative design, should be used as a model for future LID developments and the basis for future case studies which aim to preserve pre-existing hydrology in developing watersheds. The Woodlands is a convincing example of how beneficial human development can be accomplished without compromising the natural environment.

The analysis in this study of small sub-areas within a watershed could be significantly improved if measured flow data was available at the discharge points. This would alleviate some uncertainty that was encountered during this study as to which prediction was more accurate.   A more certain estimate of peak flows may allow one method to be proven superior over the other. If the physics-based distributed model predictions are closer to the true flows, then further advancement in computer processing and GIS data could enable models, such as *Vflo™*, to become even more powerful tools for hydrologist and urban planners.

5 Appendix

Appendix A.



AVERAGE VELOCITIES FOR ESTIMATING TRAVEL TIME
FOR OVERLAND FLOW
FOR FORT BEND COUNTY, TEXAS

Source: Urban Hydrology for Small Watersheds, Technical Release No. 55, Soil Conservation Service, January, 1975.

FIGURE 2-6

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